Space Elevator Systems Architecture

An initial top-level view of a space elevator concept through space systems architecture and space systems engineering

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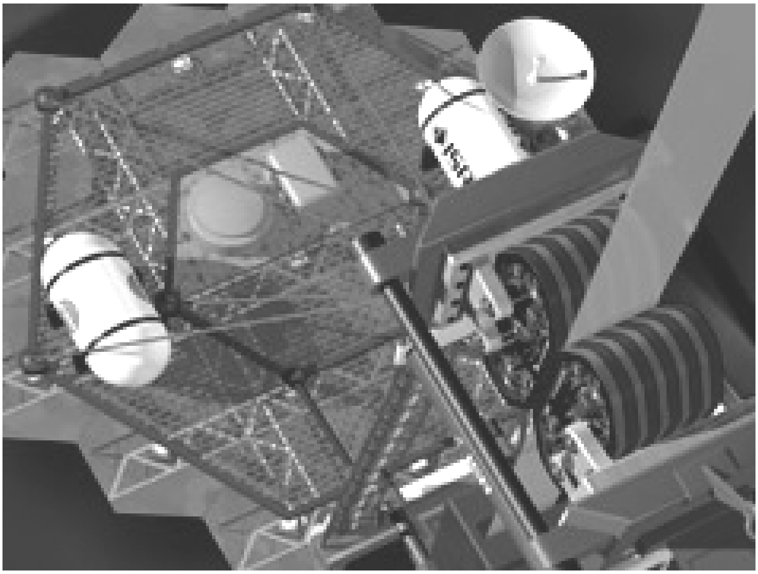

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Cover Figure: Space Elevator System by Bradley C. Edwards
Title Page Figure: Space Elevator Climber by Bradley C. Edwards

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PREFACE

This book provides a new look at a future Space Elevator project from a Systems Architecture perspective. The application of this discipline to a mega-project ensures a real engineering view from the top. The system of systems that is considered during this discussion is a "revolutionary way of getting from Earth into space, a ribbon with one end attached to Earth on a floating platform located at the equator and the other end in space beyond geosynchronous orbit. A space elevator will ferry satellites, spaceships, and pieces of space stations into space using electric lifts clamped to the ribbon, serving as a means for commerce, scientific advancement, and exploration."[1] Major engineering studies are identified, explained, and placed in perspective, within the context of a Space Systems Architectural approach that deals with critical regulatory, financial, international, and, of course, engineering factors.

Development of a space elevator is directed at the cost of access to space. The current and historic approach of launching satellites has become more refined, but is still described as "Building rockets… always on the edge of chaos."[2] This approach has two serious handicaps: only a small fraction of launch mass on the pad gets to orbit; and, the fuel and structures are all consumed. These handicaps lead to large inefficiencies and tremendous costs. One goal of the space elevator is to leverage an initial investment into access to space infrastructure and then take advantage of a routine transportation mode. The parallel to a bridge is evident, as the climber only consumes renewable energy. This leverage should lead to $100 (US dollar) per kilogram in the near future, and eventually, to $8 per kilogram after multiple space elevators are operating. The rocket

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[1] Web news release from Second International Space Elevator Conference – Sante Fe New Mexico – 12-15 September 2003.

[2] Robert Sackheim, "Panel Discussion," The Space Elevator 3rd Annual International Conference, 30 June 2004, Washington, D.C.

infrastructure will change to being one around planets (and returning to Earth) while the "to orbit" infrastructure will be low cost, readily accessible, and open to all. George Whitesides stated… "Until you build an infrastructure, you are not serious."[3] The space elevator is designed to be ***THE*** space access infrastructure to orbit, the Moon, Mars and beyond.

To understand ***why*** a space elevator is needed, three components of the discussion must be present:

- **The human spirit needs no restrictions:** Once the Apollo 8 picture of the Earthrise from the lunar orbit was broadcast, the world was sensitized to our limitations and the realization that we were on a fragile planet. We must soar beyond our boundaries and expand into the solar system. With an economical infrastructure, this can be accomplished.
- **The realization that chemical rockets can not get us beyond Low Earth Orbit:** The rocket equation requires that approximately 80% of the mass at the launch pad is fuel and 14% is structure, control equipment and other essential elements of a launch vehicle. This leaves roughly 6% for payload (mission satellite) that must be raised 300 km and moved up to 7.9 km/sec in velocity. The tyranny of this rocket equation must be broken to enable commercial expansion into space.
- **The recognition that the "*Space Option*" will enable solutions to Earth's current limitations:** The space option is an alternative that is now open to humanity with access to space. Resources, expansion area and future hopes ride with the launch of each satellite and exploration activity. By lowering the price to orbit and ensuring an infrastructure that does not throw away 94 % of its mass every time it launches, expansion can be real. Three important missions will be discussed that take advantage of the creation of an inexpensive and reliable access to space: solar power satellites, exploration of the solar system, and planetary protection.

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[3] Whitesides, George, "Panel Discussion," The Space Elevator 3rd Annual International Conference, 30 June 2004, Washington, D.C.

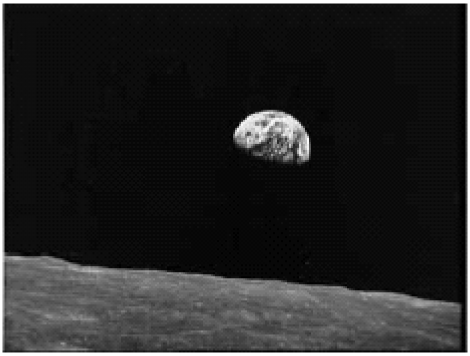

Figure 1.0, First View of the Fragile Ear 1

The purpose of this book is to make the space elevator arena a little better understood, through the use of space systems architecture and space systems engineering. It is directed toward decision makers, engineering managers, regulators, financiers, engineers, and technicians. There is a large need in our space industry to understand this dynamic "to orbit" arena, especially as mega-project launch programs have all gone through financial problems. Not only will success rest on the engineering brilliance of the teams, regulatory breakthroughs in the international arena, and management of "mega-projects" in a timely manner; but, also in the customer enthusiasm toward lower cost to orbit and financial contracts for global service. This look at a Space Systems Architectural approach, as applied to the space elevator project, will assist the reader in the future with similar major endeavors.

This book lays out the initial top-level view of a space elevator through a space systems architecture approach for space mega-projects in both an academic and a practical manner illustrating the steps, tradeoffs, complexities and successes/failures. Dr. Rectin, in his book *Systems Architecting*[4], recognized that over time "...great architectures required creative individuals capable of understanding and resolving problems of almost overwhelming complexity." As a result, "Architecting... (has become)... both a science and an art. The former is analysis-based, factual, logical, and deductive. The latter is synthesis-based, intuitive, judgmental, and inductive. Both are essential if modern systems architecting is to be complete."[5] Current challenges in developing large complex systems, such as new and

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[4] Rechtin, Eberhardt, *Systems Architecting*, Prentice Hall, Englewood Cliffs, NJ, 1991.

[5] Ibid.

cheap access to space, indeed require both of these skills. Especially important is artistic talent to understand customer desires from different global cultures and engineering skills to meld these within current technological feasibility. Architecting, as described by Webster, is "the art and science of designing and building a system."[6] A space systems architectural process develops and evaluates systems; and, is characterized by three early steps of the development cycle: capture needs and requirements, develop architectural concepts, and evaluation and review. Three more steps follow, which emphasize system engineering and program management: engineering design, production, and customer acceptance. Space Systems Architecture, as a discipline, is a relatively new phenomenon.

A top-level introduction of a space elevator includes looks at the project motivation, cost trades, regulatory issues, political issues, and technical considerations; including space elevator size, climber size, survival/risk reduction options, technical complexity, ribbon design, and elevator power needs. Application of the space systems engineering discipline allows an early look into the complexity of the system trade spaces and shows the current applications approach. Major issues are laid out in trade study style to provide easy access to key information backed by references, tables, equations and cost/benefit analyses. Critical understanding arises when key systems drivers are identified and laid out in such areas as ribbon design, ribbon manufacturing, space elevator deployment, market growth pattern, customer (client) needs, and basic systems engineering.

The book is organized in eight chapters:

Chapter I: Introduction – This first chapter will describe a space systems approach as well as provide a consistent space elevator theme. In addition, mega-projects will be defined. A common vision will be shown to ensure that systems' complexity does not become unmanageable.

Chapter II: Space Elevator Concept – The basic space elevator concept will be described along with the current maturity of the project. What is the status of the ribbon material and design? How far along are the orbital dynamics? How high will the space elevator reach? In addition, the maturity of the project will be discussed.

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[6] *Webster's New Collegiate Dictionary*, G&C Merriam Co., Springfield, Ma. 1961.

Chapter III: Space Systems Architecture View – The academic discipline of Systems Architecture is a product of the last decades of the 20th century. In addition, a practical approach to Space System Architecture is expanded to include three architecture views; operational, systems, and technical. One of the reasons for the development of this discipline was the growth of complexity in space systems toward mega-projects. One architectural view will be presented to place the mega-project into perspective. The example used in this book, a space elevator, is a future mega-project which could open up space akin to the way railroads opened up continents.

Chapter IV: Space Systems Engineering Approach – The first major task of the Chief Systems Engineer is to work with the stakeholders, customers, clients and potential investors to determine their needs, or refine requirements. The discipline of systems engineering is presented with the perspective of a major project, a space elevator. During this process, problem definition is pre-eminent, understanding of major portions of the development process is outlined, and requirements are discussed (e.g., manufacturability, launch ability, and operational needs). The refinement of the motivation of the project usually leads to a common vision and agreement on how to proceed. The final few pages reflect the major issues for trade studies that must be conducted.

Chapter V: System Engineering Trade: Space Elevator Survival – The confidence to go forward with a space elevator will derive from engineering expertise and an expectation that risk areas can be controlled. This leads to the determination that survival of the space elevator depends upon a risk management plan dealing with space debris, orbiting satellites, meteorites, and terrestrial threats such as lightening and hurricanes. This chapter deals with a plan to change the current perception of the space arena to that which expects survival as an engineering reality reinforced with some straightforward approaches applied in a systematic manner across altitude regimes.

Chapter VI: System Engineering Trade: Anchor Infrastructure – This chapter illustrates the systems engineering approach by examining the critical issue of where to locate the attachment point for the space elevator and how to form the infrastructure supporting this mission. Two key questions will be addressed (along with others): Where to locate (with special emphasis on sea or land based) and how far off the equator?

Chapter VII: System Engineering Trade: Operations – This chapter evaluates the needs of the operators and applies the systems engineering process to assist in the mega-project design. Early involvement from operations expertise will ensure more efficient operations once the commercial aspects start.

Chapter VIII: To the Moon: A Visionary Architecture – One of the significant advantages of the space elevator is that you can get a free "toss" out of the Earth's gravity well from altitudes beyond geosynchronous. This chapter outlines the advantages of this strength and shows an architecture for lunar exploration exploiting the space elevator.

Chapter IX: Road Forward – Can you imagine $100 per kilogram to space? How do we get there and which engineering approaches are the most viable? Who should invest? How to make it an international project? What is a reasonable timeline? Many questions are on the table and must be evaluated to ensure that the project can be successful.

The authors would like to thank the many people who have challenged their minds on a topic with many unknowns. The diversity of concepts and experiences has led to a phenomenal knowledge pool in a space elevator community that is remarkable. We would especially like to thank Dr. David Raitt for his research on mega-projects and their costs. In addition, we thank the participants in NASA's Broad Area Announcement response dealing with the Exploration Initiative incorporating a space elevator for the use of their proposal (Bradley C. Edwards, Ben Shelef, Dr. Paul Spudis, Dr. Heinz-Hermann Koelle, Dr. Michael Duke, Ms. Pamela Luskin, Ms. Patricia Russell, Dr. Hyam Benaroya, Dr. David Raitt, & Dr. Bryan Laubscher).

In addition, the authors would like to thank Eric Westling for his marvelous ability to see where the book can be best improved. His role as partial editor of this book reflects his expertise in not only the technical world of space elevators, but his understanding of how to put a project together.

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Each of the authors thank Dr. Bradley Edwards for his special help on this project, to include drafting portions of chapters and assisting in revising phrasing and presentations. Of special help was his sharing of figures and pictures from his last few years of work on space elevators.

This book is a result of the authors' efforts across more than a calendar year. Their many decades of wisdom and hard-won expertise from experiences, both failures and successes, have been placed in full view of the reader. Not all subjects were addressed to the same level of detail; however, the intent is to provide that "big picture" look at Space Systems Architecture as applied to a space elevator. This objective was discussed extensively and met by these authors with some late nights and intense analyses. Through the year of review, there was an effort to be consistent and eliminate errors and ambiguities. If some remain, please let us hear from you.

Co-Authors Cathy Swan, Ph.D.
Peter A. Swan, Ph.D.

CHAPTER I – INTRODUCTION

1.0 Dreams of Many

Space has generated excitement and stimulated the human psyche toward the fulfillment of dreams, expressions of hope, and the realization that there are ideas larger than the individual and worthy of pursuit. Millions have dreamed of going on an adventure to places exotic and historic; for many that dream has been to travel to space or other planets. With the advent of a space elevator, possibilities skyrocket and dreams just may come true. The difference is that space adventures could be affordable -- $100 per kilogram. How much do you weigh? At that fee, you might want to start that diet and savings account simultaneously.

A likely scenario is that a couple on an adventure can ride a space elevator at a leisurely pace to reach the 100 km altitude hotel for a few days of rest, relaxation and an out-of-this-world view. The return could be no less spectacular. The couple could choose to spiral back down to Earth in Burt Rutan's upgraded Space Ship One with its "shuttlecock" flutter through the upper stratosphere leading to a normal airplane-like landing. Dreams are made to be fulfilled. A space elevator could enable some of those dreams.

This book will start with a discussion of the WHY of a space elevator and then broaden into a set of processes that should be considered for the program development, systems engineering and systems architecting. This book will also describe a space elevator from the view of a Space Systems Architect and Space Systems Engineer. Discussions will relate the difficulties inherent in combining dreams with engineering realities. This natural conflict will be expressed in the form of major engineering studies comparing choices with needs of the customers, clients, and stakeholders. In the space elevator program, the technical challenges will be substantial and the customers so demanding that managers must take into account advancing technologies as well as the changing social environment. Advances in materials and choices of approaches will be fluid during the next ten years or so, and drive the Space Systems Architect and the Space Systems Engineer to leave the engineering spaces open and ensure documentation of choices for future evaluation. A key creative tool to global and far reaching projects is brainstorming. This particular approach requires an open mind to ideas being generated. Much of this book will show issues and identify risk factors that could intimidate the less confident architect or systems engineer. The only comparison for confidence is that architects and systems engineers for the Panama Canal, Golden Gate Bridge, and transcontinental railroads all ran into challenges beyond their experience set; and yet, they accomplished great tasks. A space elevator will require a team and partnership at a scale now called *mega-project*. This term is used to describe projects of a magnitude greater than a billion dollars and/or ten years in development. These types of projects require additional disciplines to maintain direction and vision while instilling confidence and hope.

1.1 Why Build the Space Elevator?

Because we must! The human spirit and the human condition have a rare opportunity as we enter the 21st century to leapfrog current limitations. The human spirit was given a tremendous boost as we recognized that the Earth was alone in the void of space and borders between countries could not be seen from orbit. The image of Earth from Apollo 8's lunar orbit has been described as a turning point in humanity's understanding of itself. Secretary General of the United Nations, Mr. Kofi Anann, stated,

> When one of the early missions produced the first photographs of the Earth taken from space, it revealed a planet without national borders, a fragile orb dependent on a delicate web of resources and ecosystems, a single sphere that is the common home for all of humanity.[7]

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[7] Annan, Kofi, *Impact of Space Activities upon Society*, European Space Agency, 2005. pg. 15.

Three elements of the space elevator why discussion are:

- The human spirit should have no restrictions
- Chemical rockets cannot move humanity beyond Low Earth Orbit
- The *Space Option* will enable solutions to current limitations through extraterrestrial missions

1.1.1 Human Spirit Expansion This moment in time provides the opportunity for people to re-evaluate the human spirit and add a choice called the *Space Option.*

> ***Space Option:*** Help solve Earth's problems with resources from extra-planetary sources. Change humanity's view from a planetary one to a series of solar system views.

This concept implies that humanity will move beyond the restrictions and limitations of the global condition. The Earthrise photo also emphasized the critical "one-world" issue – This is all we have – Let us not mess it up or use it up! As a result, this world-changing event – a simple photo of the Earthrise as seen from the Moon – energized conservation efforts and gave hope of alternative resources. Futurists during the 1960s and 70s, base upon the Club of Rome activities, projected limitations to growth. The *Space Option* has opened up alternatives not well understood in the 20th century. With it, the human race can see beyond the limitations of a single world and expand beyond low Earth orbit. As such, the human spirit can quite literally reach for the stars. The operation of a single, and then multiple, space elevators will create an opportunity for philosophers to reach out and embrace a *Space Option* which could rescue humanity from the limitations of a single world with expanding populations and limited resources.

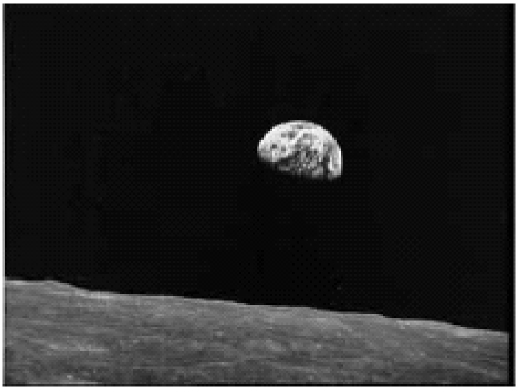

Figure 1.1, First View of Earth 1

1.1.2 Chemical Rocket Engines Have Failed The first fifty years of space exploration were all based upon the chemistry of rocket engines. This phenomenal reach of humanity into the galaxy enabled communications satellites, major storm warning systems, footsteps on the Moon, investigations of Mars surface rovers and countless other successes. The tremendous cost of launch, just to get into space, will drive our choices of what will be accomplished in the future. The costs of a space shuttle after 2005 will be beyond comprehension when one takes the budget for the years remaining (2005-2010) and divides it by the number of launches remaining. This simple calculation shows a cost of greater than $1.5 billion per launch. Less expensive standard launches exist, such as Ariane ($ 140 million per launch), Atlas V ($135 million per launch), Delta IV ($135 million per launch), Proton ($70 million per launch), and Sea Launch ($85 million per launch). Even the new launches that advertise low cost through commercial processes cost tens of millions of dollars when placing large loads into space. The reality is that the cost to launch a chemical rocket will never be inexpensive because we "throw it away." Even "reusable" rockets throw away approximately 80% of the mass at the launch pad as consumed fuel. The following analogy puts this quandary into perspective.

Car Cost Analogy
A person buys a car from Japan The car is shipped to him by car carrier across the Pacific [to be truly analogous, the car carrier ship must only load approximately 6% of the mass of the ship (launch vehicle) as payload(cars).] The car is off-loaded in Los Angeles The car carrier ship is then taken out to Catalina and <u>sunk</u> The question is: How much would the new car cost if we used the chemical launch/satellite model of economics?

The issue with chemical rockets is that it takes 94% (approximately, depending on variation of launch vehicle) of the launch mass on the pad to raise the altitude of the payload satellite to 300 km and raise the velocity to 7.9 km/sec (17,600 mph). Approximately 80% of the mass at the pad is chemical fuel to be consumed – leaving 20% for "motors, propellant tanks, propellant pumps, support structures, guidance and control systems, recovery systems, and finally, payload."[8] The need for a thrust to weight ratio of greater than one at the pad and the tremendous problem of gravity and drag ensures that the chemical rocket answer is not cost effective as a basic infrastructure to the stars. The problem is simple and will not be solved by single-stage to orbit or re-usable rockets; chemical rockets require consumption of 94% of initial launch mass. That infrastructure does not remain for the next launch. A space elevator will change the equation with an infrastructure that is maintained and re-used over the lifetime of the project. Just imagine an infrastructure to deliver objects into space for $100 per kilogram!

1.1.3 Significant Missions The advent of an infrastructure for delivering affordable payloads to space will enable missions only dreamed of now. Each of the flowing missions will alter the condition of humanity. They are no less than revolutionary.

<u>Support to Extra-Planet Activities</u>

A space elevator to support activities beyond low Earth orbit will be a watershed in human exploration. The ability to move masses, on schedule with almost no chance of loss and for $100 per kilogram, will

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[8] Jurist, John, Sam Dinkin, David Livingston. "When Physics, Economics, and Reality Collide – The Challenge of Cheap Orbital Access," an engineering draft paper. pg.4.

enable a transportation industry similar to the advent of the transcontinental railroad or the autobahn/interstate highway systems. Some very interesting parallels can be developed between the infrastructures of a transcontinental railroad and the space elevator. Table 1.1 relates the facts as outlined by Stephen Ambrose in Nothing Like it in the World[9] and the projected strengths of a space elevator infrastructure sending mass "to the planets and stars."

Ambrose noted in his book that "President Andrew Jackson traveled no faster than Julius Caesar," and that… "thoughts or information could [not] be transmitted any faster than in Alexander the Great's time."[10] By 1869, human movement had advanced to a heart stopping 90 kilometers an hour while word and ideas had leaped to light speed, telegraphed across a continent. No wonder Horace Greeley called the transcontinental railroad "The Grandest and Noblest enterprise of our age."[11] The transcontinental railroad was described as "the road (that) would be of a size unprecedented anywhere in the world, and it would go in advance of settlements through an area whose remoteness and climate discouraged or completely precluded rapid migration."[12]

Table 1.1, Railroad & Space Elevator Comparison

NY to San Francisco by railroad	Pre- Golden Spike	Railroad Operations
	Via Panama 3/14 – 8/30 /1849 Via Cape Horn 7/14 – 1/26 /1849 Across the plains approx. 6 months Multiple deaths along the way Mail costs dollars per ounce Trip cost about $ 1,000.00	Government Awarded Loans to build Right of way over public land Five alternate sections per mile awarded Trip time – approx. 7 days Trip cost - $70.00 Mail costs at pennies per ounce
Space Elevator	Pre-Operations	Space Elevator Operations

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[9] Ambrose, Stephen. *Nothing Like it in the World*, Simon & Schuster, New York, 2000.

[10] Ibid. pg. 357.

[11] Ibid. pg. 82.

[12] Ibid. pg 64.

	Launch costs Commercial: $25,000/kg Government $40,000/kg Space Shuttle - $1.4 billion per Launch Rate About 80 launches per year Probability of Success – 95% Launch on time rate – approx 0%	Lift Costs $100 per kilogram for materials Human launch by rockets until mature space elevator refined Lift Rate Five carriers on space elevator Each carrier at 13 tons payload Week trip – estimate 1/day Probability of Success – estimate 100% Launch on time rate – estimate 100%

The idea of easy space exploration starts with the development of an infrastructure that provides routine and inexpensive velocity, dependent upon altitude. The concept is that the space elevator reaches out beyond geosynchronous orbit with a solid track upon which to place interplanetary exploration. As a carrier gains altitude, the velocity increases (see Table 1.2). At the surface of the Earth, the rotation is approximately 470 meters per second [24 hour day and 40,074 kilometers circumference] – yes, when you are SCUBA diving in the Galapagos, you are traveling at 470 m/sec. As the space elevator infrastructure raises the carrier, the velocity of a spot on the elevator is calculated from the rotation of the Earth and the moment arm - altitude plus radius of Earth. Table 1.2, Space Elevator Altitude Release Points, shows the release point velocities as the spot on the elevator varies.

Velocity = length (radius + altitude) x rotation rate of Earth

Some interesting insights are gained as one does this calculation (Table 1.3, Insight into Altitude Locations). Because of this phenomenon of linearly increasing kinetic energy as climbers gain altitude on the space elevator, three items of note occur:

1) One must be consistent in using altitude instead of orbit when defining where a climber is located on the space elevator,

because one is not in an orbit that misses the Earth much of the trip.

2) An altitude of 23,390 km[13] is required for elliptical characteristics to facilitate an Earth orbit. Additional energy would be required to circularize and to add inclination for a low Earth Orbit (LEO). However, the energy required to create a circular LEO, by way of a space elevator and in-orbit maneuvering, would be significantly less than lifting the spacecraft by rockets to that altitude. In addition, low thrust/high efficiency options (such as ion engines, tethers, aero capture or solar sails) could also be utilized.

3) Beyond GEO altitude, the ellipse rapidly expands. Both potential energy and kinetic energy are increasing rapidly. As a result, escape from the Earth's hold can be achieved at 46,749 km2 altitude with locations natural for flights to the Moon, Mars and the outer solar system. Indeed, by going just beyond GEO altitude, an interplanetary probe (or human transportation vehicle) can release its grip on the Space Elevator and float on its new trajectory to its solar system destination.

Table 1.2 Altitudes and Velocities

Circular Orbit Vel. (km/sec)	Release Point Alt-Spc.Elev (km)	Velocity @ Altitude (km/sec)	Energy @ Altitude (km^2/sec^2)	Altitude at Perigee or Apogee (km)	Comments Pg – perigee Atmos - atmosphere
7.91	0	0.47	-62.39	-6.E+03	Pg below surface
7.73	300	0.49	-59.57	-6.E+03	Pg below surface
7.35	1000	0.54	-53.88	-6.E+03	Pg below surface
6.90	2000	0.61	-47.39	-6.E+03	Pg below surface
5.92	5000	0.83	-34.69	-6.E+03	Pg below surface
4.93	10000	1.19	-23.62	-6.E+03	Pg below surface
4.32	15000	1.56	-17.43	-5.E+03	Pg below surface
3.75	22000	2.07	-11.90	-1.E+03	Pg below surface
3.66	23412	2.17	-11.02	1.E-01	Pg in Atmos
3.62	24000	2.22	-10.67	6.E+02	Perigee
3.46	27000	2.43	-8.98	5.E+03	Perigee
3.07	35786	3.07	-4.73	4.E+04	Circular orbit
2.93	40000	3.38	-2.88	9.E+04	Apogee
2.87	42000	3.53	-2.02	1.E+05	Apogee

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[13] Chobotov, V. "The Space Elevator Concept as a Launching Platform for Earth and Interplanetary Missions," 2004 Planetary Defense Conference: Protecting Earth from Asteroids, AIAA, Orange County, California, Feb. 2004.

2.74	46700	3.87	-0.02	2.E+07	Apogee
2.74	46742	3.87	0.00	3.E+08	Apogee
2.74	46745	3.87	0.00	-4.E+11	Hyperbolic orbit
2.21	75000	5.93	12.71	-1.E+05	Hyperbolic orbit
1.89	105000	8.12	29.40	-1.E+05	Hyperbolic orbit
1.74	125000	9.58	42.86	-1.E+05	Hyperbolic orbit
1.60	150000	11.40	62.47	-2.E+05	Hyperbolic orbit

Radius of Earth = 6378 km mu of Earth = 398600

The beauty of an infrastructure for transportation of space exploration vehicles crosses many disciplines, but boils down to:

Support to Extra-Planetary Activities

Routine, inexpensive, non-chemical launch toward a planet of choice, on schedule.

Table 1.3, Insight into Altitude Locations

Fact	Insight
Low Altitude releases do not result in enough energy to be in orbit. The potential and kinetic energies are small. [less than 23,390 km altitude]	Release point of payload at low altitude results in re-entry to Earth's atmosphere unless additional energy is added.
Mid to high altitude releases result in elliptical orbits with perigee above atmosphere and apogee at release point altitude. [between 23,390 and 35,786 km]	To gain low Earth orbit, energy must be taken at perigee to lower apogee. To gain Global Positioning Satellite (GPS) like orbit, must change state of energy to match speed and altitude for circular orbit.
Release at geosynchronous altitude [35,786 km]	Circular orbit "sits" next to elevator Natural location to work
Release beyond geosynchronous [greater than 35,786 km]	Perigee is release altitude with apogee higher for orbital operations[14] Uses only mechanical energy to propel toward planets (think crack the whip) Perigee of escape hyperbola Toss to Mars at 56,898 km Toss to Jupiter at 119,063 km Toss to inner planets also possible

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[14] Edwards, Bradley C. & Eric A. Westling, *The Space Elevator*, BC Edwards, Houston, Tx, 2003 p. 95.

	Note: all calculations for planetary tosses must account for motion of planets as well.

Energy for All

The dichotomy around the globe for delivering a fair share of energy resources to all is based upon the history of mankind, distribution of wealth, country economic status, country based energy infrastructure and weather impact. These limitations have been seen as North-South, East-West, have's – have not's, oil rich – oil starved, nuclear capable – fossil fuel, and high technology – low technology. The future of oil is not unlimited, with estimates until major limitations ranging from near term (5 years) to longer term (150 years). Demand exceeding supply will affect the future of our oil based energy infrastructure.

A large body of knowledge exists on a solution to a very large portion of this problem, both energy source and energy distribution. Tremendous work has been accomplished over the last 30 years; and, has been revolutionary in thinking, technologically exciting and rewarding, economically analyzed, and proposed around the world. The concept is simple:

Orbit solar collection satellites
Collect renewable solar energy
Beam to almost anywhere on the surface (70 N to 70 S latitudes)
Establish receiver antenna farms as close as possible to energy requirements
Deliver energy – almost anywhere, continuously, and at phenomenally low prices

For the first time, the finance costs for energy will be above production costs, while remaining within market pricing and margins. Not only would the creation of energy be based upon a constant re-usable source, but the architecture of a system with multiple large satellites could enable distribution to any location on the globe. Think of some of the potential benefits:

Reduction of pollution from oil based industries
Vast economic growth based upon inexpensive energy
Development around the globe near receive stations

Less dependence on oil producing countries
Africa could leapfrog the 20th century oil based energy economy

The natural question is why hasn't this solution been employed, especially as gasoline has broken the $60 per barrel cost. The answer is simple. The cost to launch humongous solar collection and energy redirection satellites make the project unaffordable at $25,000 per kg. The choice of using an infrastructure, like a space elevator with freight charges of $100 per kilogram, will revolutionize the economics of space based solar power systems. The space elevator will ***Enable*** this energy solution for some of the Earth's major issues. The impact on the human condition will be dramatic, with energy availability and economic growth.

Energy for All

This solution will enable energy to be available to anyone, anywhere for very low cost and pollution.

Earth Protection

Today the Earth is as vulnerable to a giant asteroid as it was 65 million years ago when the dinosaurs disappeared (a current theory about the demise of dinosaurs includes an asteroid impact creating a global cataclysmic event). Currently, countries around the world are cooperating with a network of sensors to identify "Earth crossing" bodies (comets and asteroids). This initial step in the protection of the Earth from another cataclysmic event is excellent; however, two more steps must be initiated:

(1) Design and develop asteroid busters

(2) Launch to rendezvous (in a timely manner)

International progress to achieve either step is extremely slow; however, the consequences are so unthinkable, that leaders around the world are starting to be concerned and are taking notice. The significant advantage that a space elevator infrastructure provides is two-fold:

(1) Guaranteed delivery to orbit (safe elevator vs. chemical rocket probabilities)

(2) Storage at proper location with tremendous flexibility as to "free velocity" when released from long rotating infrastructure.

The development of a space elevator infrastructure will enable Earth protection infrastructures to develop in a timely manner.

Earth Protection

The ability to reliability store and launch multiple asteroid busters at appropriate altitudes will encourage progress in this vital mission.

1.1.4 Expectation vs. Reality The expectation of American leadership during development of the Inter-continental Railroad was that it would lead to immense trade with China and India. This expectation was wrong and reality struck! The main development from continent spanning railroad was a phenomenal internal development of America.[15] The expectation for space exploration over the last 50 years has been varied with peaks and valleys. The current administration at NASA has a charter to "kick-start" an exploration program back to the Moon and on to Mars. The public expectation deals with this very large challenge while wondering what the personal impacts will be: pollution, taxes, jobs and the future. It seems that there is a tremendous parallel with opening up a continent and opening up the solar system. To have a successful venture, the launching of thousands of tons of material must be reliable and cost effective. Today, that expectation is $25,000 per kilogram for launch to orbit. That would lead to $125 billion [five thousand metric tons x $25,000] cost for launch vehicles alone. When the space elevator has been completed, the price for five thousand tons of material would be only $500 million, or 0.004% of the current cost because of an infrastructure approach vs. chemical fuels. This dramatic lowering of launch costs will enable the human spirit to soar and the human condition to improve through cheap energy, new resources, and renewed opportunities.

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[15] Ambrose, Stephen. *Nothing Like it in the World* Simon & Schuster, New York, 2000.pg. 370-1.

1.2 Mega-Project Comparison[16]

Getting things into perspective is instructive and illuminating. A space elevator is estimated to cost $6.2 billion (B) to develop, launch, construct and become operational. How does this figure compare to some other aerospace systems and non-space spending patterns? Some examples are given below from aerospace and other fields. No attempt has been made to be comprehensive – just a few figures are derived from the course of everyday reading. Due to its size and scale – 100,000 km in length, 15 years and roughly $6.2 B - the space elevator is a mega-project on par with other major engineering construction efforts such as bridges, towers and railway tracks. The amount involved to build the space elevator is not at all out of proportion when other mega-projects are considered.

Aerospace Mega-Projects: Forecasts of cumulative expenditures from 2005 through decommissioning for the International Space Station after 2016 is a total of nearly $60 B – an amount that is approximately the same as the shuttle development program. NASA's budget plans call for $6.6 B for Project Constellation – the Crew Exploration Vehicle that will take astronauts back to the Moon. The X-30/NASP cost about $7.5 B. The cost of Prometheus is said to be $1.5 B. The last shuttle, Endeavor, completed in May 1991, cost $2.1 B. The cost of ESA's cometary spacecraft Rosetta was $1 B for the 165 kg payload, orbiter and 100 kg lander.

Boeing is planning to spend some $7.5 B on development of its new 7E7 airliner. Meanwhile, the US Army has just cancelled a two-seater scout helicopter project after over 20 years of development and $8 B in costs with no production aircraft in sight – closeout costs could be another $3 B.

Building Mega-Projects: There is a constant urge to build the world's largest structures. No sooner is one project finished than another is on the drawing boards. Italy aims to beat Japan's record for suspension-bridge length, Dubai plans to surpass Taiwan's world's tallest building, and Japan is working on another that will dwarf these. Located in a region known for its hurricanes and earthquakes, the Taipei 101 tower is currently the world's tallest building. Developed by the Taiwan Financial Center Corp. the 101 story building is 508 meters high – 56 m higher than the previous record holder, the twin Petronas Towers in Kuala Lumpur. The cost of the Taipei 101 tower

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[16] Raitt, David and Bradley Edwards, “The Space Elevators: Economics and Applications,” adapted from draft, at International Astronautical Federation Congress in Vancouver, Oct 2004.

is $700 M, with each of the express, pressurized elevators to move between the 101 stories costing $2 M.

Not to be outdone, Dubai is planning a massive residential and hotel tower estimated to cost between $1-2 B. The building will be some 610 m high and, like the Taipei 101 tower, will have to withstand some severe wind speeds causing vortex shedding and shaking. The small footprint of the building necessitates a single 11,000 voltage power line and the elevators will ascend (though not descend) at 1100 m per minute.

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

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

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

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

Another mega construction project has been the Channel Tunnel – an underground rail link between England and France. The possibility of a tunnel linking the two countries had been discussed for over 200 years and digging actually started several times, but it was not until 1987 that the project finally got underway. It was completed in 1994 at a cost of approximately $13 B.

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

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

An even more ambitious maglev project is the vacuum tube train from New York to London. As currently envisioned, a neutrally buoyant tunnel, with the air pumped out, submerged 45-90 m beneath the Atlantic Ocean and anchored to the seabed would allow a maglev reaching speeds of up to 6500 kph to cross in an hour. Since above-ground sections would be cheaper to built than underwater, the proposed route would pass through northeastern Canada and touch land in Greenland and Iceland before reaching the British coast. Even so, the project is estimated at $25-50 M per kilometer or between $88-175 B for the New York-London link.

1.3 Vision Development

Pursuit of a mega-project requires technical knowledge, funding, political support, and management skills; however, one critical component increasing the probability of success is an exciting vision to pull the program together and drive it forward. The development of a vision is an extremely complex task. This should be done with an initial cadre of people on the project trying to determine the best way to lead with a concept, idea or thrust. The establishment of a vision is critical to constant forward motion for the team. It should be accomplished early in the development cycle, prior to establishment of any hard requirements. The sooner the better.

1.3.1 Recommended Vision for the Space Elevator At the beginning of this chapter we mention the millions that dream of traveling to space. There are many more that dream of a better life and good future for their children. Many of these people fear that their dreams will not come true. Fear and hope are powerful drivers. The Apollo program was driven by fear of loosing our way of life to the Soviet Union and hope of a new space age and all its benefits.

For the space elevator we have the same types of visions that motivated Columbus, the transcontinental railways and the U.S. interstate highway system; creating easy access to new worlds, new discoveries and endless horizons for our future. We have easy access to the whole of Earth, globalization has allowed this. We know its bounty and its bounds. We also know that these limits will impede our progress and even erode the status quo. The space elevator gives us the road to limitless opportunities and through the limitations we fear.

1.3.2 Recommended Vision

Space Elevator Vision

The space elevator gives us the road to limitless opportunities while opening up the solar system.

1.4 Space Systems Approach

When a team decides to take on a mega-project, the complexity immediately grows with the realization that defining the scope of the problem is an immense task. In the last century, engineering projects moved from garages and bicycle shops to small factories to conglomerates spanning the globe. Even with the reach and complexity of a project such as the space elevator, it boils down to a few individuals who maintain discipline in the process and ensure that the team progresses. This vision-driven activity usually falls onto three leaders: Space Systems Architect, Space Systems Engineer, and Space Systems Manager.

1.4.1 Space Systems Architect The Space Systems Architect is the vision creator or maintainer, brainstorming instigator, heuristic reasoning sharer, engineering leader, and confidant of clients, customers and stakeholders. [further expanded in Chapter III, Space Systems Architecture] He or she appreciates the broad reach of their responsibilities.

Table 1.4, Space System Architect's Responsibilities on the Space Elevator Program

1 Identification of customers, clients and stakeholders
2 Definition of needs to be fulfilled by a space elevator
3 Establishment of a systems vision
4 Identification of engineering potential
5 Recognition of "show stoppers," both engineering and social
6 Refinement of the initial solutions
7 Merge reality and dreams
8 Development of architectures

Goal: Enable a Space Elevator through cross-arena insight

Rectin, in his book *Systems Architecting*[17], recognized that over time "...great architectures required creative individuals capable of understanding and resolving problems of almost overwhelming complexity." As a result... "Architecting... (has become)... both a science and an art. The former is analysis-based, factual, logical, and deductive. The latter is synthesis-based, intuitive, judgmental, and inductive.

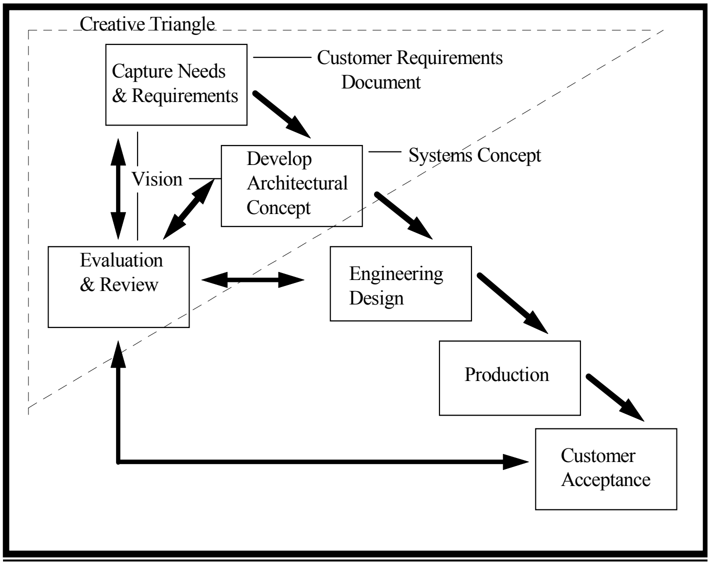

Figure 1.2 Pragmatic Systems Engineering Principles[18]

Both are essential if modern systems architecting is to be complete."[19] Current challenges in developing large complex systems, such as new and cheap access to space, indeed require both of these skills. Especially important is artistic talent to understand customer desires from different global cultures and engineering skills to meld these within current technological feasibilities. The academic approach to a space systems architectural process develops and evaluates systems; and, is characterized by three early steps: capture needs and requirements, develop architectural concepts, and evaluation and review. As shown in Figure 1.1, three more steps follow this *Creative Triangle*; engineering design, production, and customer acceptance.

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[17] Rechtin, Eberhardt, *Systems Architecting*, Prentice Hall, Englewood Cliffs, NJ, 1991.
[18] INCOSE pamphlet on Systems Engineering, INCOSE web site 2003.
[19] Rechtin, Eberhardt, & Mark Maier, *The Art of Systems Architecting*, CRC Press, New York,1997.

1.4.2 Space Systems Engineer The Space Systems Engineer is a fulfiller of requirements, trade space owner, lead systems engineer across all disciplines, insurer of compliance with processes and standards, and driver of manufacturing, production and deployment. [This is further expanded in Chapter IV, Space Systems Engineering] He or she understands the complexity of a mega-project and especially respects the pragmatic systems engineering principles.

Table 1.5, Pragmatic Systems Engineering Principles

1 Know the problem, the customer, and the consumer
2 Use effectiveness criteria based on needs to make systems decisions
3 Establish and manage requirements
4 Identify and assess alternatives to converge on a solution
5 Verify and validate requirements and solution performance
6 Maintain the integrity of the system
7 Use an articulated and documented process
8 Manage against the plan

Goal: Enable a Space Elevator
through engineering insight

The history of systems engineering goes back into the mega-projects of World War II, such as bombers, aircraft carriers, logistic routes and communications infrastructures. During the early days of nuclear power development and space exploration, systems engineering became a critical element in their successes. In addition, during the remarkable days of the 50s and 60s with commercial businesses expanding rapidly, systems engineering was required to develop vast projects such as AT&T communications infrastructures around the world. As it has matured, systems engineering has consumed many disciplines into its skill set, to include operations research, systems management, system modeling and simulation, decision analysis, requirements development, software management, industrial engineering, and risk management.

Basic Systems Engineering Definitions:[20] The International Council on Systems Engineering (INCOSE) has developed some definitions that are applicable to our discussions. They are shown below.

System	An interacting combination of elements to accomplish a defined objective. These include hardware, software, firmware, people, information, techniques, facilities, services, and other support elements.
Systems Engineering	An interdisciplinary approach and means to enable the realization of successful systems.
Systems Engineer	An engineer trained and experienced in the field of Systems Engineering.
Systems Engineering Processes	A logical, systematic set of processes selectively used to accomplish Systems Engineering tasks.
System Architecture	The arrangement of elements and subsystems and the allocation of functions to them to meet system requirements.

1.4.3 Architecture vs. Systems Engineering Systems architecture is becoming routine in large, complex, system of systems design and development activities while systems engineering has been ingrained into the design process with an international society leading the process (International Council of Systems Engineering – INCOSE). A quick comparison chart will help ensure that appropriate tasks fall where they are best accomplished. Fitzgerald proposed a new term that signifies this separation – Architecture Engineering.[21] Table 1.5 shows a quick look at significant differences between these two disciplines.

Table 1.6, First Order Comparison

System Engineering	Architecture Engineering
Assemble the compatible	Assemble the incompatible
Sub-optimization is inevitable	Optimization is an imperative

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[20] *Systems Engineering Handbook,* INCOSE, Version 2.0, July 2000, p. 11.

[21] Fitzgerald, Michael, "Architecture Engineering," a draft briefing, May 2005.

DII / COE	Open architecture
Clean Interfaces	Intelligent Interfaces
Modeling, Simulation and Analysis lets you see how it operates… anomalies are solved	Modeling, Simulation and Analysis projects operational alternatives – anomalies are avoided
System Performance	Mission Success
Block Upgrades	Adaptive Evolution
System to Segments to….	Domains and sub domains to…
Built-in Test Equipment	Agents and Synoptic Monitoring

COE Common Operating Environment
DII Data and Information Integration

1.4.4 Space Systems Manager Owner of schedule and project activities, ensurer of staffing excellence, financial monitor, test manager, deployment manager, and follower of requirements satisfaction.

Table 1.7, Systems Management Major Responsibilities

1 Develop and Maintain Systems Management Plan
2 Develop and Maintain Systems Schedule
3 Select Appropriate Tools
4 Perform Technical and Project Management
5 Establish Standardized Methodology

Goal: Enable a space elevator
through management skills

1.4.5 Systems Trade-Off Studies This book will reach across all three disciplines required to build a mega-project (architecture, engineering, and management) with additional reach into manufacturing, deployment and operations. During the mega-project development process, there are many times when too many variables are involved in making a decision. The existence of many unknown values, and even unknown unknowns, is a consistent state of affairs early in a new program. In other words, early in the program the systems engineer does not even realize the values that need to be quantified before progress can be made. To move forward in this situation, the systems engineer, architect of the project and program manager must all be able to discuss issues and choose a path with the most promise of success. One excellent methodology used exhaustively in the engineering process is the trade-off study. This is a tool that presents as much information as is known at the time and allows the appropriate individuals to make decisions or recommendations so the project can move forward. An additional benefit is that the documentation of the trade-offs is available for future review, improvements or even revision.

Systems trade-off studies involve many factors with the goal of presenting the facts. This is usually accomplished in the form of tables, matrices, or graphs. The term "trade study" represents a trade-off analysis focused on a question. Usually the trade study uses a process of trading between many variables. In the very early phases of a mega-project there are few solid answers to questions, mostly "best guesses." Table 1.8 shows some of these major questions that must be addressed by a space elevator team.

Table 1.8, Systems Engineering Trade-off Studies

1	Existing rockets vs. new construction of large lifter
2	Electric propulsion inorbit vs. conventional chemical rockets
3	Ribbon strength safety factor of two vs. higher
4	Single 20 ton ribbon vs. dual 20 ton ribbons
5	Constant cross section profile vs. variable design
6	Laser beaming vs. other power systems
7	50 ton capacity vs. 20 ton capacity ribbon

The term "trade space" is defined as "the set or range of feasible alternatives to be compared to achieve a solution balanced with respect to system effectiveness, cost, schedule, risk, and potential for evolutionary growth."[22]

The utility of a trade-off study is that it presents the information in a manner that allows analysis across multiple variables and many estimates. The use of tables is a favorite approach with rows associated with the facts and columns labeled "characteristic description," "benefits," and "concerns." The tabular presentation is especially beneficial when relating a series of facts. The systems engineer needs to evaluate the importance of each fact and how it impacts the analysis being conducted. Another method of comparing

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[22] Pennell, L.W.&F. L. Knight, *SMC Systems Engineering Handbook.* Draft 15 April 2005. pg. 100.

values and ideas is to have a graph with characteristic values for each known value. This is a very good way to compare two engineering approaches and their costs. The horizontal axis would be years of the project while the vertical axis would be the cost of the project that year. The data would be presented for case A, B and C as curves on the chart. The use of trade-off studies is an excellent tool that assists decision makers as they are presented with information which is conflicting and confusing. Graphical or tabular presentation forces participants to compare and contrast alternatives for the future. The trade spaces (scope of the analysis – such as cost vs. year or single ribbon vs. multiple ribbons) that occur across a mega-project seem immense and impossible to tackle. The use of trade studies is a methodology that can significantly help decision makers on their way to a successful project.

1.5 Book Structure

Throughout this book, our purpose is to identify and explain major segments, potential risks, engineering processes, and social factors in a manner helpful to the Space Systems Architect's determination of an optimal path for this mega-project. To accomplish this goal, the processes of space systems architecture and space systems engineering will be explained. Issues will be highlighted, discussed, traded with other risks and solutions proposed across the infrastructure. The chapter layout is as follows:

Chapter I: Introduction – Essentially a setting of the stage for discussion of mega-projects with potential for solving the "to space" problem.

Chapter II: Space Elevator Concept – This chapter will start with the history of the concept and will bring together the current plans for the project with the analyses already completed. The maturity of the project will be addressed and major issues identified.

Chapter III: Space Systems Architecture View – This chapter will assess the project from the view of a Space Systems Architect. This melding of artistic talent and engineering savvy will ensure that customers' desires are traded with engineering possibilities. Both an academic and a practical approach will be shown.

Chapter IV: Systems Engineering Approach – This chapter will look at the systems engineering process, with its hierarchical approach and its requirements based initiation. The whole team can focus toward a vision supportive of space elevator development when the issue of why the space elevator is well understood. The many trade space arenas that are currently being addressed will be shown in table format to lay the groundwork for the scope of the program.

Chapter V: Systems Engineering Trade: Space Elevator Survival – This chapter will trade the threats facing an elevator with techniques for risk reduction. A large matrix can be used to capture the priorities associated with the methodologies for risk reduction proposed over the full height of the space elevator.

Chapter VI: Systems Engineering Trade: Anchor Infrastructure – This chapter will address the location of the space elevator attachment to the Earth. The logical location would be at the equator, with small acceptable variations, and either at sea or on land. These choices will be evaluated and traded as well as the analyses of other issues required for the safety and survivability of the space elevator.

Chapter VII: Systems Engineering Trade: Operations – This chapter will assist the space systems architect, engineer, and manager in their quest to have an efficient and cost effective operation. To ensure this, the systems engineering approach is used to identify unique requirements for operations that could/should have an impact upon the design.

Chapter VIII: To the Moon: A Visionary Architecture – This chapter will show the tremendous advantage leveraged by the inclusion of the space elevator in the Lunar/Mars Exploration Initiative. Not only is the cost reduction (by a factor of 250) remarkable, but the ability to transport any size or shape upon the ribbon without "shake-rattle-roll" of launch will result in a radical change in design approach.

Chapter IX: Road Forward – The last chapter will lay out a road map that stretches toward an operational date.

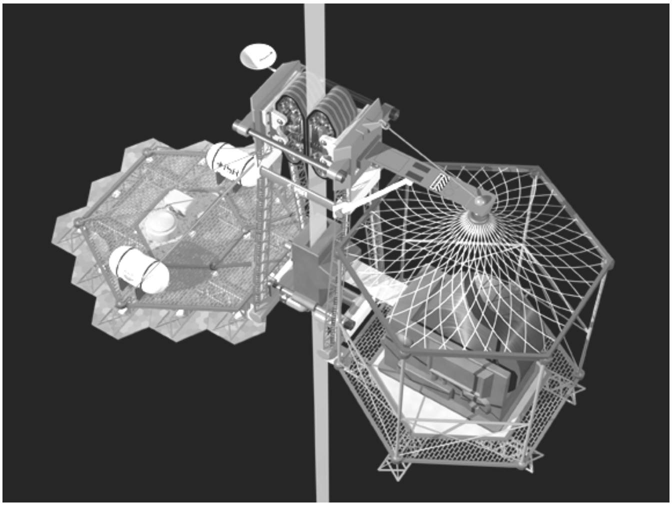

Figure 1.3, Space Elevator Climber[23]

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[23] Edwards, Brad, from work at Institute for Scientific Research, Inc. 2004

CHAPTER II – SPACE ELEVATOR CONCEPT

2.0 Space Elevator History[24]

The idea of a "stairway to heaven" is as old as the Bible, and includes the Tower of Babel and Jacob's Ladder. Modern thought on space elevators goes back to Konstantin Tsiolkovski,[25] a school teacher in St. Petersburg, Russia, who did a "thought experiment" on a tower into space. Tsiolkovski imagined tall towers on the sun and planets, and realized that, because of their rotation, gravity would decrease as you ascended such a tower, reversing at the altitude where a satellite would have a period the same as the rotation period of the body. Here the gravitational and centrifugal forces on a body in geosynchronous orbit are in balance. Tsiolkovski calculated the synchronous altitudes for the five visible planets and also the sun, but he concluded that building a real tower into orbit was impossible.

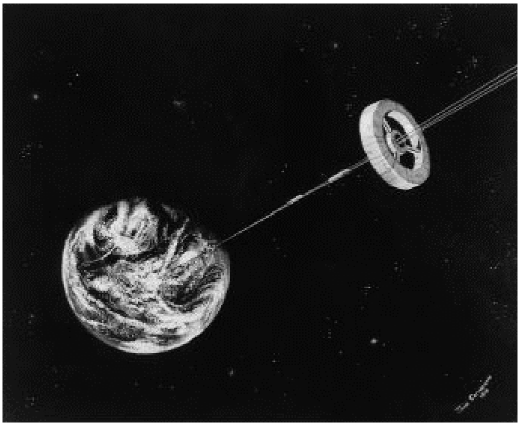

Figure 2.1, Space Elevator, an Air Force Painting, 1975

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[24] History section 2.0 contributed by Jerome Pearson, 8 Aug 2004.

[25] Tsiolkovski, K. E., *Speculations of Earth and Sky*, and *On Vesta*, (science fiction works, 1895). Moscow, Izd-vo AN SSR, 1959.

In the 1950s, Leningrad engineer Yuri Artsutanov discovered how to build a real structure for the space elevator, but did not publish an engineering article. His ideas appeared in a Sunday supplement to *Pravda* in 1960,[26] and their significance was not then recognized in the West. In 1966, a group of oceanographers led by John Isaacs at the Scripps Institute re-discovered the concept, but they proposed such a thin wire that it would be cut by micro-meteoroids almost instantly, and was therefore completely impractical.[27]

Jerome Pearson, an aerospace engineer with the Air Force Research Lab near Dayton, Ohio, independently discovered the concept and published it in the international journal *Acta Astronautica*.[28] This technical article made the international aerospace community aware of the space elevator for the first time. An Air Force painting of Pearson's space elevator is shown here, with capsules moving up and down from the space complex in synchronous orbit. His discovery included using the space elevator for zero-net-energy space launching, and for launching payloads from the elevator tip to reach other planets without requiring rockets. He also was first to examine the dynamics of actually lifting payloads up the elevator, and found limitations on the speeds of ascent, akin to the critical velocities of a rotating shaft and the periodic loads from soldiers marching on a bridge.

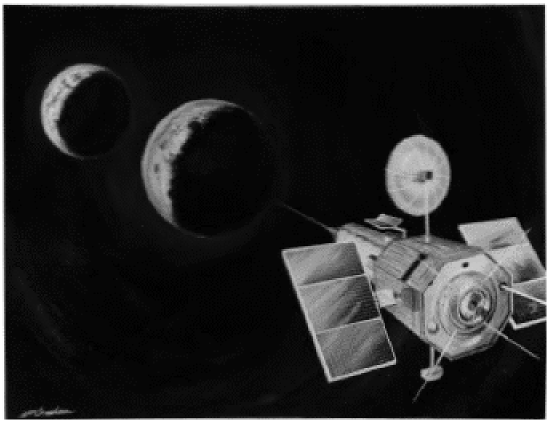

Figure 2.2, Space Elevator, an Air Force Painting,1975

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[26] Artsutanov, Y., "Into the Cosmos by Electric Rocket," *Komsomolskaya Pravda,* 31 July 1960. (Contents described in English, Lvov in *Science,* **158**, 946-947, 1967.)

[27] Isaacs, J., Vine, A. C., Bradner, H. and Bachus, G. E., "Satellite Elongation into a true Sky-Hook," *Science* **151**, 682-683, 1966.

[28] Pearson, J., "The Orbital Tower: A Spacecraft Launcher Using the Earth's Rotational Energy," *Acta Astronautica* **2**, 785-799, 1975.

Pearson later extended the space elevator idea to the moon, using the Lagrangian points as balance points in lieu of a stationary orbit. He discovered that such a "lunar anchored satellite" could be used to bring lunar materials into high Earth orbit cheaply. +-Interestingly, Artsutanov[29] published a paper on a lunar space elevator just one month later than Pearson, without either author being aware of the other! John McCarthy and Hans Moravec of Stanford University had been thinking along similar lines, and seeing the Pearson orbital tower publication, led Moravec to propose rotating space towers unconnected to a planet or moon, for catching and throwing space payloads to different orbits. Artsutanov had also proposed this concept earlier, but it was not known to Moravec. [30]

In 1978, Arthur C. Clarke illustrated the idea of a space elevator in his novel The Fountains of Paradise.[31] His main character built a space elevator close to the equator on a mountain top with similar engineering traits to today's concepts. Paul Penzo then extended the idea of space elevators and tethers to Phobos, the closest moon of Mars. He also proposed using a rotating tether to attach a spacecraft to asteroids, to change their orbits without rockets, like a gravitational assist.

One fundamental problem of building the space elevator is the phenomenal strength of materials required to support its mass over the 35,800-km height to geostationary orbit. Artsutanov and Pearson recognized that carbon "whiskers" representing perfect-crystal structures, might be one way to achieve the required strength. When carbon nanotube structures were discovered, it was realized immediately by Richard Smalley at Rice University in Houston, Texas and by Boris Yakobson at North Carolina State University that these super-strength materials would make the space elevator possible.

The next big step was interest of NASA's Marshall's Advanced Projects Office with ideas such as the space elevator. David Smiterman published a conference proceedings that was entitled, "Space Elevators: An Advanced Earth-Space Infrastructure for the New Millennium."

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[29] Artsutanov, Y., "Into the Cosmos without Rockets," *Znanije-Sila* **7**, 25, 1969. Moravec, H., "A Non-Synchronous Rolling Skyhook," *Journal of the Astronautical Sciences* **25**, 307-322, 1978.

[30] Pearson, J., "Lunar Anchored Satellite Test," AIAA Paper 78-1427, August 1978. - Pearson, J., "Anchored Lunar Satellites for Cislunar Transportation and Communication." *Journal of the Astronautical Sciences*, Vol. XXVII, No. 1, pp. 39-62, Jan/Mar 1979. – and -Artsutanov, Y., "Railway 'Moon-Earth'," *Technika Molodishi*, No. 4, p. 21, 1979.

[31] Clarke, A. C., *The Fountains of Paradise*, Harcourt Brace Jovanovich, New York, 1979.

Using these ideas and materials, Bradley Edwards proposed a practical scheme for constructing a space elevator about the Earth, and received NASA funding for a study. His study resulted in a surprising conclusion: The space elevator could be developed within 15 years. His studies included calculations and analyses on fiber composed of epoxy-bonded carbon nanotubes, propulsion techniques, climber designs, location of base infrastructure, and cost/schedule estimates. "In 1999, we began examining what was a science fiction concept from a new direction, what is possible in the near future. At the time if we began a search of the internet we would have returned roughly 200 references to the space elevator. Last week it was well over 150,000. Part of this growing interest is the book that was published in 2002, as a result of a NIAC funded study, *The Space Elevator*. There are now hundreds of people working on some aspect of the space elevator.[32] " The work to date has been to establish a baseline design and address the major technical issues. Though there has been little funding for these efforts over the last 5 years, work has been progressing. Many of the efforts are independent but in communication with each other. This means that parts of the designs are transferred and used across efforts but not all. This innovation across diverse development is remarkable with significant leaps in concepts occurring during every meeting. Multiple conferences have been held to bring together these diverse groups of scientific investigators. Table 2.1 shows the breakout across the globe during this emphasis on the engineering side of the space elevator.

Table 2.1, Conferences and Symposia

Title	Location	Date
Space Elevator Conference	Seattle, WA	8/02
2nd Annual International Space Elevator Conference	Sante Fe, NM	9/03
3rd Annual International Space Elevator Conference	Washington DC	6/04
International Astronautical Congress (2 sessions)	Vancouver, BC	10/04
Space Exploration 2005 (Space Elevator Workshop)	Albuquerque, NM	4/05
International Astronautical Congress (2 sessions)	Fukuoka, Japan	10/05

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[32] Edwards, Brad, personal communications, on 1 Aug 2004.

2.1 Space Elevator Systems Concept

A basic space elevator has many systems working within the family of systems. These would include at least the ribbon, the satellite that deploys the ribbon, the launch vehicle that places the satellite into geosynchronous orbit, various climbers, power generation systems, communications systems and of course a counterweight at the end of the ribbon. Each of these will be discussed as the system of systems is described; however, a short description of some primary elements is shown below:

Ribbon: The ribbon must be made of a material that can withstand its environment and operational stresses. This would include all of the threats to the system as well as tensile stress inherent to support itself. It turns out that if the ribbon can support 130 GPa of tension, a space elevator can not only support itself, but 5 major climbers at a time. The materials being tested in the laboratory at this time have surpassed that level and promise a ribbon that can withstand the environmental and operational stresses necessary. The current ribbon design is of a one meter wide ribbon, paper thin, consistent in shape from the anchor to the counterweight.

Space Elevator Anchor: The anchor for a space elevator has many possible engineering paths. It turns out that one of the biggest issues is location; shelter on land or at sea. The trades for the anchor reach across political, investment, engineering, weather, and operational issues. A simple solution could be that a heavy ship can act as a base for operations and move the ribbon out of harms way. Much more will be discussed, especially during the chapter on base leg design.

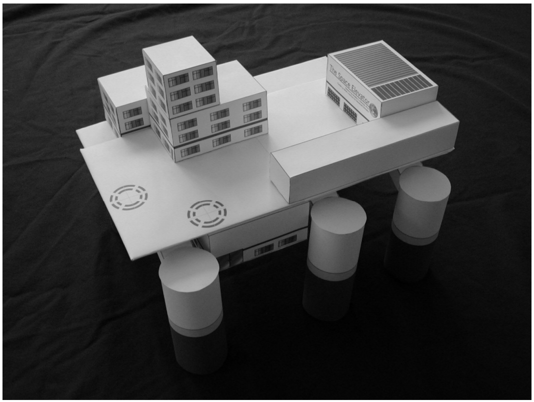

Figure 2.3, Space Elevator Anchor [33]

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[33] Edwards, Bradley, image from previous work at Institute of Scientific Research, Inc.. 2002.

Climber: The variety of climbers will surprise even the early believers in a space elevator. There will be ribbon weavers, ribbon repairers, ribbon safety inspectors, logistical trams, commercial climbers, human rated climbers, hotels, launch ports, etc. However, key to their success will be the requirement to have an open standard so that all the climbers can work on the space elevator. The analogy would be to the railroad's standard width of its rails. Anyone can put a train on the rails if they adopt the standards of the rails. A similar approach must be used to ensure compatibility between ribbon and climbers.

Energy Source: Power will be supplied through different mechanisms, leading to electrical engines that move the climbers. Ideas range from laser and radio frequency energy from the ground, to solar or nuclear power for non-interruptible power. Design trades will lay out options and systems engineers will move forward toward proposed solutions.

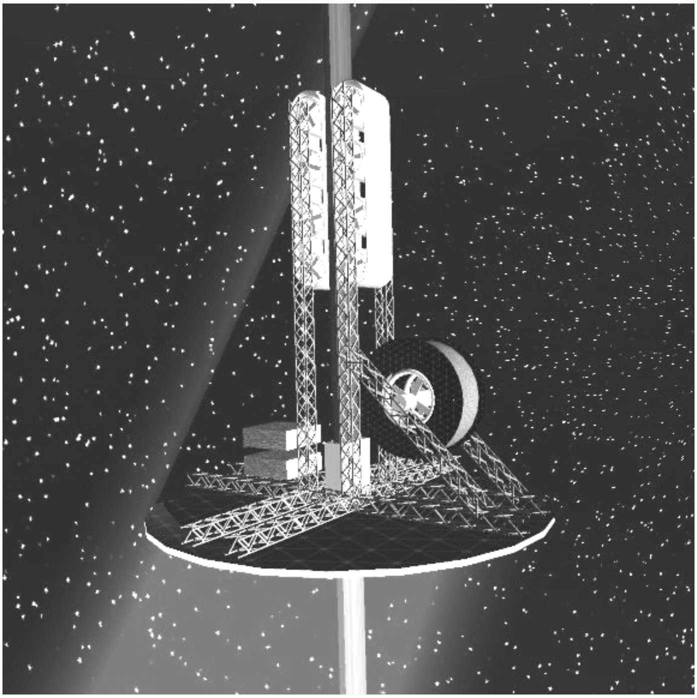

Figure 2.4, Climber[34]

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[34] Edwards, Bradley, image from previous work at Institute of Scientific Research, Inc. 2003.

2.1.1 Phases of the Development Figure 2.5, Development Phases, shows the layout of the incremental process of deploying a system in space, expanding from single ribbon to robust ribbon with logistics climbers, and finally human rating of the system. In addition to the breakout of a design, the chart at the lower portion of the figure shows the start and end time frames as well as the process steps to achieve that phase of development.

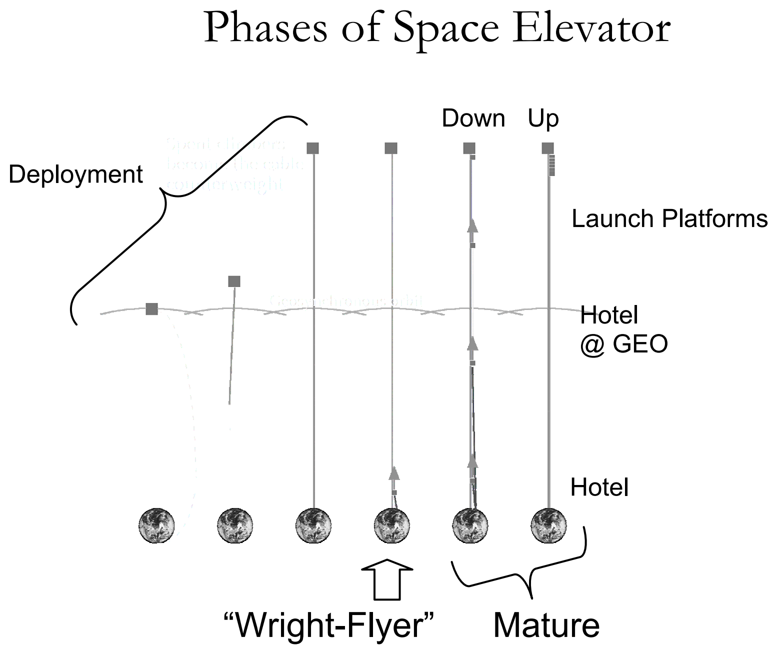
2.1.1.1 Deployment Phase This phase has to do with being a "satellite with center of mass in orbit." When it establishes a connection to base stations, it will transition to a space elevator connected to the Earth. This first phase has a requirement to launch a space elevator into orbit, deploy the ribbon down/up, ensure counterweight supports angular momentum needs, dynamically control the ribbon as it falls toward the surface, ensure survival during deployment, and finally attach to the surface of the Earth.

2.1.1.2 Wright-Flyer Space Elevator Phase This development phase starts the unique "real" activities of a space elevator – running items up the ribbon. This phase will include initial stabilization of the ribbon; activities to strengthen and protect a single strand; deployment of stations for multiple locations (low altitude – 100 km, mid altitudes – 2,000 km and 18,000 km, geosynchronous altitude – 36,000 km, and solar system launch points >37,000 km); development and deployment of ribbon climbers (logistics tugs, people climbers, repair/upgrade scooters, etc.); and, integration of essential support infrastructure such as communications, command and control activities.

2.1.1.3 Mature Space Elevator Phase This phase begins with the first human rated capability and continues through commercial success. This would include multiple "way points" for customers, to include Earth orbiting launch nodes, hotels, GEO launch node, Lunar launch node as well as Mars and beyond launch nodes.

2.1.2 Elements of a Space Elevator System A space elevator system is composed of multiple segments that have complex interactions integrating various mission activities. To fully visualize this system in a simplified manner, segments are shown in "bite size" elements that can be understood, defined, requirement sets can be established, interactions developed and communications described.

Some of these could be: Launch vehicle, deployment spacecraft, ribbon and spool payload, counterweight infrastructure, command and control, power, anchor, climbers, and ribbon manufacturing.



	Deployment Phase	**Wright-Flyer Phase**	**Mature SE Phase**
Start	Partial funding	First Ribbon Climber	First Human Climber
End	Solid anchor with stable 1st strand	First Human Climber	Continuous Commercial success
Steps	Authorization to initiate Funding Profile Design Production of Segments First Launch (multiple if necessary) Deployment down and up Attachment to	Stable space elevator Run second strand for safety Run Weavers Refine Safety approach Place logistics stations at GEO Run first cargo climber Revenue producing climbers	Design Production Eliminate radiation belts Ensure safety of Space Elevator (human rating) Deploy hotels and logistics climbers First Human climber –

	Earth at anchor Stable space elevator		probably workers First commercial human climber Commercial success Hotels successful Human spaceflight to Moon and Mars Additional Space Elevators developed

Figure 2.5, Development Phases

2.2 Space Elevator Maturity

A surprising aspect of a space elevator is that the overall maturity of the components, subsystems, systems and materials is high. In fact, many items that will make up the elements of a space elevator have already been qualified for space. Other components range from needing scientific refinement through technological demonstration to engineering development. These three categories of maturity[35] are defined as:

- Scientific Refinement: The ability of mankind to discover how things work.
- Technological Demonstration: Applies science to useful projects by experimentation and testing.
- Engineering Development: Implements knowledge into repeatable and beneficial components, subsystems and systems.

The reality of developing a mega-project is that components of the design fall within all three categories and different levels of "care and feeding" must be applied. Can you imagine what the developers had to accomplish when?

Gas lamps were placed throughout London
Electricity was provided around Washington, D.C.
Telephones were installed across Canada

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[35] Westlling, Eric. Personal communications, email note, 2005.

Airplanes started carrying paying passengers around the Pacific
The tunnel was drilled under the English Channel.

Each of these had to transition parts, components, subsystems and systems from scientific discovery through technological demonstration to engineering application.

Historically, inside the space arena, NASA has defined different levels of maturity. Figure 2.6 shows the Technology Readiness Levels (TRL) for NASA projects. From an outsiders viewpoint, the TRL levels 1-3 relate to basic scientific discovery and refinement; TRL levels 4-6 to technological development; while, TRL levels 7-9 to engineering refinement and application. As shown in Table 2.2, the space elevator design is evaluated across TRL levels. When applying this NASA guidance to space elevator components or subsystems, three items show up in the lower levels of a TRL chart; ribbon material, climber (locomotion concept), and systems design.

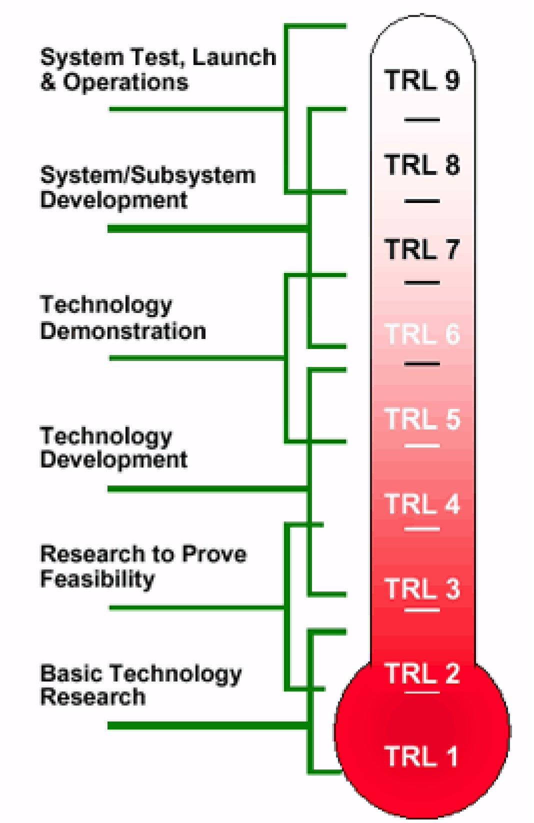

Figure 2.6, NASA Technology Readiness Levels

Ribbon Material: Material for the space elevator ribbon (estimated 130 GPa of tensile strength) does not exist at a proven TRL level 9. However, recent and rapid development of nanotube tech-nology has many engineers and scientists excited about a "near-term" material sufficient for a space elev-ator. Carbon nanotubes have gone from science fiction to science fact. The current hope is that they go from the furnace (literally) in the laboratory to manufacturing by several leaps over current technologies. This leap from science through technology development to manufacturing must be in a timely manner to enable a space elevator. Laboratory tests have shown the tensile strength of carbon nanotubes reach in excess of 200 GPa. However, this is once again inside the laboratory and with minor lengths of material. The engineering and materials challenge of moving from 4 cm of carbon nanotubes to 100,000 km is currently being addressed. Scientists and materials engineers are hopeful that the appropriate material for a space elevator will soon appear for mass production. A prediction discussed at the 3rd Annual International Space Elevator Conference in Washington D.C. was that a material with sufficient characteristics for a space elevator could be demonstrated in sizable lengths in late 2005 or early 2006.

Table 2.2, Estimated Segment TRLs

Segment	TRL Level	Comment
Launch	9	Routine to launch to GEO altitude
Deployment Satellite	8	Routine to operate at GEO altitude with constant connectivity to the operations center; however, deploying a long ribbon of this length has not been attempted
Ribbon Material	2-4	Ribbon material has moved from the laboratory to the materials development facilities. Many different approaches are being attempted to produce the carbon nanotubes at reasonable prices and in a manner compatible with continuous ribbon production.
Anchor	9	Sea based operations would leverage the tremendous oil platform experience while logistics centers exist for all transportation approaches, such as rail, train or air.
Climbers	4-7	Depends on the design and needs of each climber. The weavers must be designed from basic concept while the logistics climbers could be modeled after current high speed high rise elevators. The spacecraft characteristics are well known.
Power Generation	6-9	Laser power generation at this level has not been accomplished, but seems doable with current technology. The RF power generation is a scaling up of current technology.
Human	6-8	Human rating of space vehicles is well known;

Rating		however, running elevators at high speed for 100,000 km through the radiation belts provide a tremendous design challenge.
Systems Design	6-7	Mega project integration is not trivial and needs tremendous efforts to reduce complexity and ensure segment compatibility.

Climber Design: The complexity of the ribbon interface has driven the design of climbers and keeps its maturity level between technological development and engineering applicability. Some questions are:

> How to provide sufficient friction forces to enable reliable grip at high speeds?
> How to ensure climbers stay on the ribbon?
> How to translate laser source energy efficiently into drive motor engines?
> How to design a platform that can carry 20 tons?
> How to survive in the harsh environments?
> Which methodology for friction; pinched wheels or track?

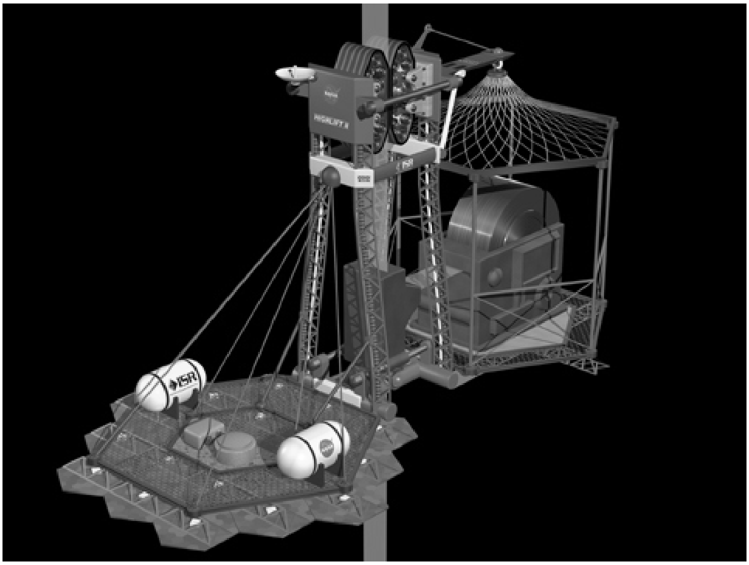

Figure 2.7, Climber[36]

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[36] Edwards, Bradley, from Institute for Scientific Research activities. 2003.

Space Elevator Systems Design No one has made an elevator that moves along a ribbon for 100,000 km against gravity, even after 47 years of spaceflight and materials designed for spaceflight. The design factors inherent in this challenge are new and must be addressed by the design team. There is no reason to believe that this cannot be achieved with solid engineering processes leading to materials production and assembly in a timely manner. A systematic design process must be applied to a family of systems that will yield an operational space elevator. This system of systems design challenge will definitely utilize the skills of the systems architect and the systems engineer.

2.3 Space Elevator Issues

The engineering team does not know all of the answers and the management team does not know all of the questions due to the complexity of a mega-project. As a result of this inherent morass of unknowns, the Space Systems Architect and project team must identify risk issues, develop plans to mitigate risks, integrate and simplify tremendous complexity, and ensure no catastrophic scenarios arise. As a starting point for the book, risk issues are briefly discussed here with much more specific identification and refinement in the remaining chapters. The risks will be separated into four categories; Selling the Project, Engineering Aspects, Testing and Deployment, and Operations.

2.3.1 Selling the Project

Engineering credibility: The number one objective of a space elevator team during this embryonic phase is the belief and passion that the mega-project can and will be done. "No show-stoppers" should be the watch word for the team. Establishing an early vision for the space elevator project will enhance the "perception of possibilities" for the investors.

Funding: Mega-projects routinely gain sufficient funding; however, the approach is always the question. Who to leverage and how to approach them are questions that will set the stage for this phase of the project. Key to this question is the estimation of the total life cycle cost and the return on investment for the stakeholders.

International: Ownership, control and access are all undetermined at this point. Each has a potential impact upon space elevator development and society as a whole. Location of the base infrastructure falls within this category.

Governmental Ownership: A key element in this issue is the early funding and commitment of governments and their support organizations. Should the military be involved? Should civil space organizations (NASA, ESA, etc.) control the program?

2.3.2 Engineering Aspects

Space Elevator Survival: One of the early questions by investors and stakeholders alike will be elevator survival. This should be addressed early and progress shown to illustrate a "Zero Cut" policy and continued survival of the family of systems. This is expanded upon in a full chapter to initiate this discussion early within the program.

Base Anchor Architecture: Many major risk issues of a space elevator are inherent in the first 2000 km of altitude. Multiple approaches must be initiated to ensure survival of this massive endeavor, to include the options of movable base anchor and ribbon dynamics control.

Environmental Threats: The design of space systems has matured over 55 years and a good understanding of the environment has developed. However, there is a slight difference with this project in that a space elevator will not be moving at high velocity though the space environment to stay in orbit. Satellite vehicle designers must realize that the environment is similar, yet unique.

Materials: Materials for the vehicles that will be traveling in space along a space elevator will parallel the current spacecraft systems' materials. This will ensure that the past history of success can be transferred. However, the material for the ribbon must be developed and is the pacing item on a space elevator project.

Dynamics of Location: The dynamics of a long space tether will be unique and must be fully understood prior to placing climbers on the ribbon. This is not a significant problem with the computing tools available. However, the impact of solar or lunar gravitation on the movement of the ribbon will need to be understood. In addition, the dynamics of moving 20 ton climbers, at 200 km/hr, will need to be studied and simulated extensively.

Size of Ribbon: The size of the ribbon will be a major trade item for many years to come. It must be robust enough to handle multiple climbers. In addition, it must support itself and ensure that a "Zero cut" policy is maintained. How wide does the ribbon have to be to handle the climbers? How thick? How strong and how resilient?

Climber Designs (people, logistics, repair/replace, etc.): The design of the climbers must be based upon an open standard such as the distance between the rails of a train. This open standard would then allow several manufacturers to supply equipment for a standard ribbon. Each of the designs must be very efficient, extremely reliable and essential expendable. The difficulty will be in setting the open standards.

2.3.3 Testing and Deployment Dynamic predictions, environmental impacts, climber interactions and safety/survival aspects all must be included in a test program. Ribbon material survival in the environment could be tested in chambers or in space. The dynamics of a space elevator will have to be simulated on the ground until the first space elevator is constructed. As the program goes forward, testing and incremental deployment will be critical to its success. Along with the development of a space elevator is a mandatory cleaning up of items such as dead satellites and rocket bodies. This deployment phase activity will have to be orchestrated within the rules of space faring nations to ensure compliance toward non-interference of a space elevator corridor [a column of space going from the anchor to the counterweight where a "keep out" zone must be mandated].

2.3.4 Operations **Humans in Radiation:** Long stays within radiation belts will require mitigation techniques with special emphasis for humans. Two approaches seem reasonable; protection of components and humans with radiation shielding, and, reducing the levels of radiation in the environment. Each of these approaches is being studied today for various exploration activities. The radiation shielding is supported by NASA and its approach for long duration spaceflight and lunar stays. The radiation belt issue is being evaluated as options for ensuring that the mega-flares from the sun do not damage sensitive components in space.

Up and Down Scheduling: A single elevator ribbon will mean complexity when de-conflicting traffic priorities.

Dynamics of Ribbon: Identifying motions resulting from multiple sources and planning for it will ensure smooth operations. Countermeasures could be designed into the operations concept to include wave cancellation.

Long Term Survival: This issue always surfaces as a major risk. As a result, throughout the book, factors dealing with space elevator integrity will be highlighted.

CHAPTER III – SPACE SYSTEMS ARCHITECTURE VIEW

3.1 Top Level

This chapter takes a top level look at a space elevator through a Space Systems Architecture approach for space mega-projects in both an academic and a practical manner. This combination leads to a better illustration of steps, tradeoffs, complexities and successes/failures for developing a space elevator. Rectin's book, *Systems Architecting*[37], is especially good at presenting the academic view of systems architecting with its reflections on the heuristic or engineering approaches. However, recent developments inside the US Department of Defense have matured systems architecting to a new level of complexity. This process has been applied to large scale systems of systems development programs, the mega-projects we have been discussing. This chapter borrows liberally from_*DoD Architecture Framework*, Version 1.0, 30 August 2003,[38] which describes the steps in the process. This practical systems architecture process establishes a framework for the systems to be developed and provides a methodology to manage complexity. This chapter describes the DoD process; however, it expresses just a few examples as applied to the Wright-Flyer portion of the space elevator development.

The approach to a space elevator development is presented from both a top level academic perspective (sections 3.1 and 3.2) and a practical perspective (sections 3.3 to 3.6). The two approaches fit nicely together as the academic side establishes major phases of a development program and describes the internal workings of these phases. The practical approach establishes visual support images of the systems to be developed with pre-determined steps to complete the architecture. This combination of academic and practical will

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[37] Rectin, Eberhart, *Systems Architecting*, Prentice Hall, Englewood Cliffs, NJ 1991, p. 156

[38] *DoD Architecture Framework,* Version 1.0, Volume I &II, 30 August 2003.

enable the space systems architect to work closely with a space systems engineer and space systems manager to identify essential elements, develop plans to create, design, and produce products, and finally, to assemble the end product item while ensuring completeness of the process.

3.1.1 Phases of the Space Elevator Development This chapter outlines the development steps for the total space elevator, while laying out the architectural views for the system of systems. However, the emphasis of this chapter is the Wright-Flyer phase of the program. The rationale for this direction is that for the mature space elevator to become reality, much effort must be expended to get to a single system that works and has the components assembled and operations initiated. This first system must also be designed and built with an eye to what needs to be accomplished in the future. Figure 3.1, compares the three start/stop stages and major steps to be accomplished.

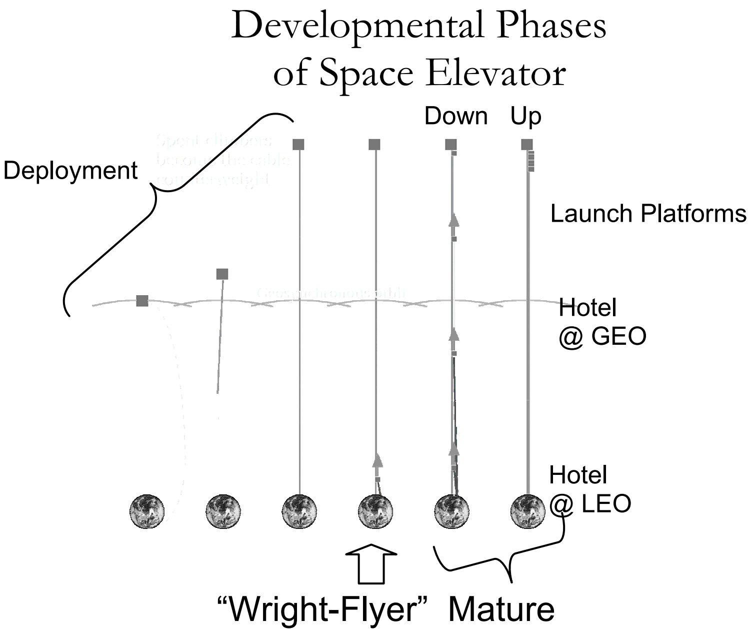

Figure 3.1, Development Phases

3.2 Space Systems Architecture Process – Academic Approach

3.2.1 Creative Process The space systems architect must be the one who encourages creativity, multiple options for different solution sets, stimulates answers from the space elevator team and ensures ideas do not arise too late to be integrated. As the focal point for the development team, the architect leads and motivates the team to address complex issues positively and aggressively. The creative triangle has been added to the traditional development flow of a mega-project so that innovation and invention occur in an orchestrated way resulting in a program that can be completed on schedule and with the allotted funding.

3.2.1.1 Vision Each successful mega-projects has a common direction for its vast and diverse team to follow. One approach to harmony on a major project is to create a vision. Everyone remembers successful visions such as: "Place a man on the Moon in this decade and bring him back safely to Earth."

Space Elevator Vision

The space elevator gives us the road to limitless opportunities while opening up the solar system.

3.2.1.2 Role of a Systems Architect The role of a space systems architect is complex, but simple. He/she is the one who must lead, stimulate, cajole, encourage, hammer, insist upon, and ensure an understanding of the project's complexities. This includes relationships with the customers/clients/stakeholders as well as systems managers, systems engineers, discipline engineers, project leads, financiers, personnel gurus and logisticians. It becomes simple when space architects remember that their role is to be the focal point and be out front so everyone can follow, copy, emulate, strive for, or catch up. Living in the world of significant unknowns while striving to reach a goal and follow a vision is very stimulating to anyone who enjoys making decisions in uncertainty with expectations of eventual success. In addition, the space systems architect must be the focal point for understanding, creating and refining the needs of the stakeholders, customers and clients. The architect must translate these needs into a more disciplined set of requirements that the space systems engineers and space systems managers can respond to and build upon. The translation of customer needs into engineering project requirements is a non-trivial exercise stretching across all phases of the program. This understanding of the artistic side of engineering development requires coordination with outside organizations and forces clean interfaces with the space elevator project. The space systems architect interacts with these diverse forces ensuring that those political, national, and international factors are considered and integrated. Along with these responsibilities for a mega-project comes the responsibility to develop the customers and the clients. The basis for this activity is usually an engineering/architectural program plan lending credence to the current concepts and approaches. The financial side must come together allowing for the continuous development of both clients and customers.

3.2.2 Architect Waterfall The expanded waterfall[39], Figure 3-2, illustrates the development cycle for a mega-project from client needs statements to operations. The role the architect plays during the full development of a space elevator must be comprehensive. The architect will interface with managers, engineers, customers, and clients ensuring that they all understand and support the vision, goals, schedule, progress to date, and risk mitigation activities.

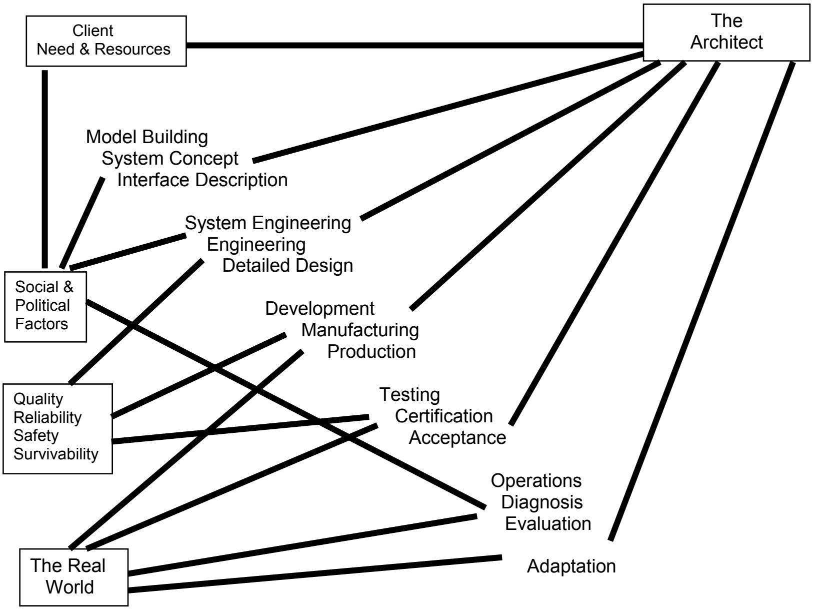

Figure 3.2, Expanded Waterfall[40]

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[39] Rectin, Eberhart, *Systems Architecting*, Prentice Hall, Englewood Cliffs, NJ 1991, pg 156.

[40] Rechtin, Eberhart, *Systems Architecting*, Prentice Hall, Englewood Cliffs, NJ 1991, p. 156.

An intriguing aspect is that a space systems architect continually interfaces with diverse backgrounds and understanding levels so their communications skill level must be remarkable. A fundamental difference between the space systems architect and the space systems engineer is the ability to work with diverse levels of technical understanding and political savvy. Dr. Rechtin describes the difference as follows: Systems Architecture "…is distinguished from systems engineering in its greater use of heuristic reasoning, lesser use of analytics, closer ties to the client, and particular concern with certification of readiness for use."[41]

This skill of addressing multiple issues from different domains simultaneously leads to tremendous tension caused by making decisions under great uncertainty (see figure 3.3). The significant, and constantly changing, trade space between performance and cost-schedule continually stresses the space architect. This trade space contributes significantly to the complexity of leading a mega-project toward a goal many years in the future.

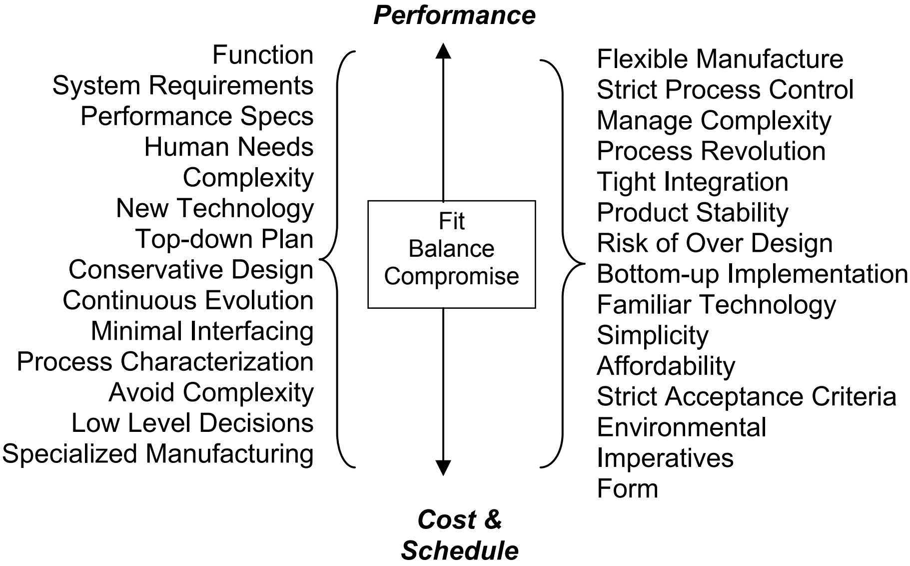

Figure 3.3 Space Systems Architect's Tension

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[41] Ibid. p. 156

Some of the more interesting trades for space elevator participants are between:

Human needs vs. Risk to Humans
Complexity vs. Affordability
Military Needs vs. Global Acceptance
3rd World Use vs. Capitalist Drive
Status Quo (Aerospace Infrastructure) vs. Progress (New Markets)
Current National Needs vs. Future National Needs

3.3 Space System Architecture Process – Practical Approach

During the last ten years, the complexity of systems has increased tremendously to the point where the term "system" is an insufficient representation. The new terminology is "systems of systems" or "family of systems" and implies that segment breakdowns leads to major systems that can be developed separately but with consistent interfaces and continual coordination. This chapter's approach is one of a mega-project where the single system of systems is a space elevator. This simplifies complex factors, by maintaining everything under one space systems architect. However, the space elevator is only one system inside a tremendous arena called access to space. This family of systems arena would include; terrestrial delivery systems, local support systems, space environment monitoring systems, space system launch infrastructure, telecommunications satellite infrastructure, and lunar/Mars exploration systems.

3.3.1 Support for Architecture Views The accepted definition of an architecture for major "systems of systems" projects is given in the DoD Architecture Framework document[42] and was derived from the DoD Integrated Architecture Panel, 1995, based upon IEEE STD 610.12.

> ***<u>Architecture</u>*: the structure of components, their relationships, and the principles and guidelines governing their design and evolution over time.**

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[42] *DoD Architecture Framework,* Version 1.0, 30 August 2003, pg ES-1

"This framework [System Architecture] supports the development of interoperating and interacting architectures. It defines three related views of architecture: Operational View (OV), Systems View (SV), and Technical Standards View (TV) as depicted in Linkages Among Views [Figure 3.4]. Each view is composed of sets of architectural data elements that are depicted via graphic, tabular, or textual products."[43] Figure 3.4 shows this interrelationship between the three views: operational view describes the mission functions between the segments; systems view identifies which systems or subsystems support the requirements for interoperability; while the technical view explains the process to execute the procurement; and, sets the standards and ensures the criteria for success are achieved.

3.3.2 Role of the Architecture Views "An architecture description is a representation of a defined domain, as of a current or future point in time, in terms of its components, parts, what those parts do, how the parts relate to each other, and the rules and constraints under which the parts function. What constitutes each of the elements of this definition depends upon the degree of detail of interest. … What those parts do can be as general as their high-level operational concept or as specific as the lowest-level action they perform. How the parts relate to each other can be as general as how organizations fit into a very high-level command structure or as specific as what frequency one unit uses in communicating with another. The rules and constraints under which they work can be as general as high-level doctrine or as specific as the e-mail standard they must use."[44] A significant role for each of the three architectural views is to organize the seemingly impossible quagmire of unknowns during the initial concept development. This is accomplished through a hierarchy of architectural views starting with the overview (AV-1); initiating the three main views (OV-1, SV-1, TV-1); and then, breaking down to the details in multiple supporting views (illustrated later in Table 3-1).

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[43] Ibid. p. ES-1

[44] Ibid. p. 1-2.

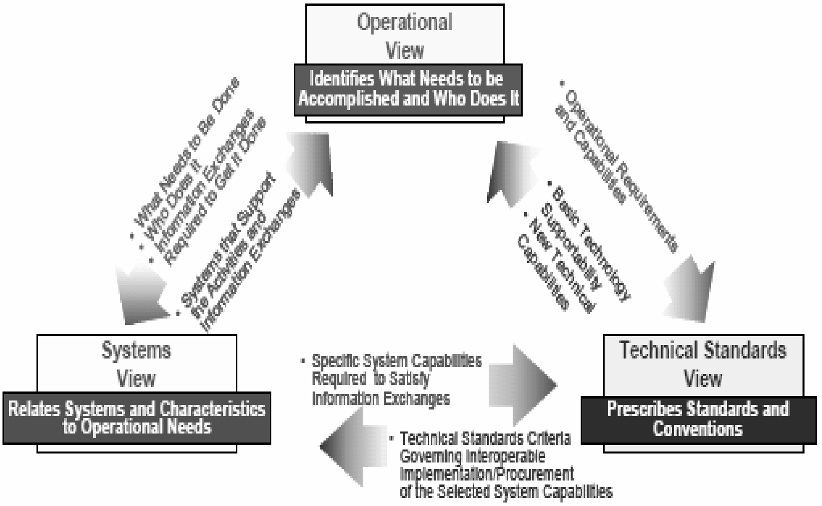

Figure 3.4, Linkages Among Views

3.3.3 Value of Architecture Views[45] One key to understanding the importance of this approach is that the value of architectures is different for each of the various users and stakeholders. The main thrust is that a well defined architecture provides phenomenal understanding of the proposed system of systems with details of interest to the customers, users, investors, stakeholders, operators, designers, systems engineers, and production teams. There are four major strengths when the architecture is accomplished early in the conceptual development of a mega-project.

Investment teams: The ability to project the system of systems in terms that can be understood by the financial community will enable the project to gain investors. Understanding the projected costs and then understanding the operations and user activities will enable investors to evaluate the value of their business decisions.

Operators of the System: Equally important is the ability to project the method of operations, players involved, support required to operate the complex system of systems, and timelines needed to accomplish the goals. The real question to the operators of the system is… “Can the system, as described in the architectural views, accomplish the goals and vision of the proposed project?”

Program Managers: The complexity of bringing a mega-project to fruition is intimidating without some structure to categorize the

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[45] *DoD Architecture Framework*, Version 1.0, 30 August 2003, p. 2-2.

unknowns. How does a team of managers orchestrate the project across complex arenas with funding profiles, schedule estimates, and risk reduction activities? Architectural views allow the program and project managers the luxury of seeing into the future with estimated timelines and funding profiles prior to committing to each phase of the project.

Customers and Users: The customer has to be able to look at the architectural views and evaluate whether the product will be sufficient for his/her needs. This estimate of the end capability and timeline for delivery is critical to gain customer buy-in.

3.3.4 Space Architecture Views

3.3.4.1 Operational Architecture View (OV): "A description of the tasks and activities, operational elements, and information flows required to accomplish or support a[n] .... operation. It contains descriptions of the operational elements, assigned tasks and activities, and information flows required to support the customer. It defines the types of information exchanged, the frequency of exchange, which tasks and activities are supported by the information exchanges, and the nature of information exchanges in detail sufficient to ascertain specific interoperability requirements. Tenets that apply to the operational architecture view include the following:

- The primary purpose of an operational architecture is to define operational elements, activities and tasks, and information exchange requirements.
- Operational architectures incorporate doctrine and assigned tasks and activities.
- Activities and information-exchange requirements may cross organizational boundaries.
- Operational architectures are not generally systems-dependent
- Generic activity descriptions are not based on an organizational model or organizational structure.
- Operational architectures should clearly identify the time phase(s) covered."[46]

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[46] *DoD Architecture Framework,* Version 1.0, 30 August 2003, pg 2-2.

Operational Architecture Role: Operational architecture views are based upon mission areas such as interplanetary launch, geosynchronous satellite repair, space launch, and human habitat. Content includes general guidelines for missions, approaches to fulfill mission techniques and procedures, goals and vision statements, concept of operations, mission scenarios, and environmental political conditions (threats, geographical attributes, political/military concerns, partnerships, etc). The essence of the operational architecture view is the expression of how a system will be operated. How do all of the segments work together to fulfill mission operations? This operational view is usually technology neutral and describes the activities to be conducted with functional areas described, such as, communications or transportation. The OV basically contains graphical and technical products defining operational nodes and elements, tasks and information flow.

3.3.4.2 Systems Architecture View (SV): "The systems architecture view is (a) description, including graphics, of systems and interconnections providing for, or supporting, mission functions. For a domain, the system architecture view shows how multiple systems link and interoperate, and may describe the internal construction and operations of [a] particular system within the architecture. For the individual system, the systems architecture view includes the physical connection, location, and identification of key nodes, circuits, networks, mission platforms, etc. And specifies system and component performance parameters (e.g. mean time between failure, maintainability, availability). The systems architecture view associates physical resources and their performance attributes to the operational view and its requirements per standards defined in the technical architecture. Tenets that apply to the systems architecture include the following:

- The primary purpose of a systems architecture is to enable or facilitate operational tasks and activities through the application of physical resources.
- Systems architectures map systems with their associated platforms functions, and characteristics back to the operational view.
- Systems architectures identify system interfaces and define the connectivity between systems.

- Systems architectures define system constraints and bounds of systems performance behavior.
- Systems architectures are technology-dependent, show how multiple systems within a subject area link and interoperate, and may describe the internals of particular systems.
- Systems architectures can support multiple organizations and missions.
- Systems architectures should clearly identify the time phases covered.
- Systems architectures are based upon and constrained by technical architectures."[47]

Systems Architecture Role: The systems architecture view addresses the full range of systems from space elevator ribbon to base configuration to roles of climbers to propulsion modules to communications infrastructure. These views depict the functional and physical automated systems, nodes, platforms, communications paths, and other critical elements supporting various space elevator missions. The systems view describes a space elevator and the connections amongst all of the elements. Usually this view is to show the different time phases of the program with several views. The systems architecture view is also used to identify the technological maturity of the segments and their components. Time phasing and technical readiness level (TRL) maturity matrices can lead to a very good understanding of how to develop, deploy and then operate a space elevator. This time phased approach (deployment, Wright-Flyer, mature) shows vividly what is now and what will be when finished – valuable for marketing the program as well as planning.

3.3.4.3 Technical Architecture View (TV): "The technical architecture view is the minimal set of rules governing the arrangement, interaction, and interdependence of system parts or elements, whose purpose is to ensure that a conformant system satisfies a specified set of requirements. The technical architecture view provides the technical systems-implementation guidelines upon which engineering specifications are based, common building blocks are established, and

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[47] *DoD Architecture Framework,* Version 1.0, 30 August 2003, pg 2-3.

product lines are developed. The technical architecture view includes a collection of the technical standards, conventions, rules and criteria organized into profile(s) that govern system services, interfaces, and relationships for particular system architecture views and that relate to particular operation views. Tenets that apply to the technical architecture view include the following:

- Technical architecture views are based on associations between operational requirements and their supporting systems, enabling technologies, and appropriate interoperability criteria.
- The primary purpose of a technical architecture is to define the set of standards and rules that govern system implementation and system operation.
- A technical architecture profile is constructed from an enterprise-wise set of standards and design rules for specific standards contained in the technical architecture and other applicable standards documents
- The technical architecture standards and criteria should reflect multiple information system implementation paradigms.
- Technical architecture profiles account for the requirements of multiplatform and network interconnections among all systems that produce, use, or exchange information electronically for a specifically bounded architecture configuration.
- Technical architectures must accommodate new technology, evolving standards, and the phasing out of old technology.
- Technical architectures should be driven by commercial standards and direction."[48]

Technical Architecture Role: This view facilitates integration and interoperability of the various segments throughout the space elevator. Utilizing a technical architecture view enables standardization and conformance to best practices across the mega-project ensuring complete systems definition and formal approval. This TV describes the minimal set of time phased standards and rules

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[48] *DoD Architecture Framework*, Version 1.0, 30 August 2003, p. 2-3.

governing the implementation, arrangement, interconnection, and interdependence of the major segments.

3.3.4.4 Product Description: Each of the tabular, textual and graphical products of the three architectural views describes particular sets of characteristics applicable to the mega-system under design. A total list of products is shown in Tables 3.2 to 3.5. However, this chapter is an introductory look at applying space systems architecture to the space elevator, and as such, only expands a top level view as it applies to the Wright-Flyer development phase of the program. This product is the Architectural View-1, Overview and Summary Information. This AV-1 presents the scope, purpose, intended users, future environment depicted, and top level analytical findings.

Table 3-1. Architecture Products[49] - All Views

Framework Product	**Framework Product Name**	**General Description**
AV-1	Overview and Summary Information	Scope, purpose, intended users, environment depicted, analytical findings
AV-2	Integrated Dictionary	Architecture data repository with definitions of all terms used in all products

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[49] Ibid.

Table 3-2. Architecture Products[50] - Operational Views

Framework Product	Framework Product Name	General Description
OV-1	High-Level Operational Concept Graphic	High-level graphical/textual description of operational concept
OV-2	Operational Node Connectivity Description	Operational nodes, connectivity, and information exchange need lines between nodes
OV-3	Operational Information Exchange Matrix	Information exchanged between nodes and the relevant attributes of that exchange
OV-4	Organizational Relationships Chart	Organizational, role, or other relationships among organizations
OV-5	Operational Activity Model	Capabilities, operational activities, relationships among activities, inputs, and outputs; overlays can show cost, performing nodes, or other information
OV-6a	Operational Rules Model	One of three products used to describe operational activity—identifies business rules that constrain operation
OV-6b	Operational State Transition Description	One of three products used to describe operational activity—identifies business process responses to events
OV-6c	Operational Event-Trace Description	One of three products used to describe operational activity—traces actions in a scenario or sequence of events
OV-7	Logical Data Model	Documentation of the system data requirements and structural business process rules of the Operational View

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[50] *DoD Architecture Framework*, Version 1.0, 30 August 2003.

Table 3-3. Architecture Products[51] - Systems Views

Framework Product	Framework Product Name	General Description
SV-1	Systems Interface Description	Identification of systems nodes, systems, and system items and their interconnections, within and between nodes
SV-2	Systems Communications Description	Systems nodes, systems, and system items, and their related communications lay-downs
SV-3	Systems-Systems Matrix	Relationships among systems in a given architecture; can be designed to show relationships of interest, e.g., system-type interfaces, planned vs. existing interfaces, etc.
SV-4	Systems Functionality Description	Functions performed by systems and the system data flows among system functions
SV-5	Operational Activity to Systems Function Traceability Matrix	Mapping of systems back to capabilities or of system functions back to operational activities
SV-6	Systems Data Exchange Matrix	Provides details of system data elements being exchanged between systems and the attributes of that exchange
SV-7	Systems Performance Parameters Matrix	Performance characteristics of Systems View elements for the appropriate time frame(s)
SV-8	Systems Evolution Description	Planned incremental steps toward migrating a suite of systems to a more efficient suite, or toward evolving a current system to a future implementation

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[51] *DoD Architecture Framework,* Version 1.0, 30 August 2003.

SV-9	Systems Technology Forecast	Emerging technologies and software/hardware products that are expected to be available in a given set of time frames and that will affect future development of the architecture
SV-10a	Systems Rules Model	One of three products used to describe system functionality—identifies constraints that are imposed on systems functionality due to some aspect of systems design or implementation
SV-10b	Systems State Transition Description	One of three products used to describe system functionality—identifies responses of a system to events
SV-10c	Systems Event-Trace Description	One of three products used to describe system functionality—identifies system-specific refinements of critical sequences of events described in the Operational View
SV-11	Physical Schema	Physical implementation of the Logical Data Model entities, e.g., message formats, file structures, physical schema

Table 3-4. Architecture Products[52] - Technical Views

Framework Product	**Framework Product Name**	**General Description**
TV-1	Technical Standards Profile	Listing of standards that apply to Systems View elements in a given architecture
TV-2	Technical Standards Forecast	Description of emerging standards and potential impact on current Systems View elements, within a set of time frames

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[52] *DoD Architecture Framework,* Version 1.0, 30 August 2003.

3.4 Approach for Developing Architectural Views

This section shows a set of four guidelines and a six step process for developing architectural views, and then applies these guidelines and processes to develop an architecture for the space elevator.

3.4.1 Guidelines for Development Table 3-5 shows the set of guidelines for building architecture views.

3.4.2 Application of Guidelines The guidelines for development of a Wright-Flyer space elevator reach across many disciplines, around the globe, and across human dreams. Table 3-5 is used as a format for approaching the space elevator development. Each principle is discussed with respect to the mega-project and how those factors apply to ensure that the developmental plan is comprehensive.

Table 3-5, Guiding Principles for Architecture Development[53]

Rule	Description
1 - Architectures should be built with a purpose in mind	Having a specific and commonly understood purpose before starting to build an architecture greatly increases the efficiency of the effort and the utility of the resulting architecture. The purpose determines how wide the scope needs to be, which characteristics need to be captured, and what timeframes need to be considered. This principle applies equally to the development of an architecture as a whole and to the development of any portion or view of an architecture.
2 - Architectures should facilitate, not impede, communications among humans	Architectures must be structured in a way that allows humans to understand them quickly and that guides the human thinking process in discovering, analyzing, and resolving issues. This means that extraneous information must be excluded and common terms and definitions must be used. Often, graphical formats are best for rapid human understanding, but the appropriate format for a given purpose must be used, whatever that format may be.

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[53] Adapted from *DoD Architecture Framework*, Version 1.0, 30 August 2003.

3 - Architectures should be relatable, comparable, and integratable across mission areas	Like the principle above, this principle requires the use of common terms and definitions. This principle also requires that a common set of architectural "building blocks" is used as the basis for architecture descriptions.
4 - Architectures should be modular, reusable, and decomposable.	Architectural representations should consist of separate but related pieces that can be recombined with a minimum amount of tailoring, so that they can be used for multiple purposes.

3.4.2.1 Guideline #1 "Architecture should be build with a purpose in mind." As a result, the actual purposes of the project must be explicitly spelled out to ensure that all of the players, investors, and stakeholders are planning for the right design and project concept.

Space Elevator Purposes

- Dramatically lower the cost, risks, and complexity of going to space
- Enable commercialization and use of space
- Develop global/space infrastructure for development of humanity's goals
- Enable solar powered satellites to be developed and provide economical, clean power for use on Earth
- Enable Lunar and Mars exploration and eventual colonization
- Enable new approaches for spacecraft design by eliminating launch loads

3.4.2.2 Guideline #2 "Architectures should facilitate communications." The management of a mega-project requires excessive care and feeding of all of the individuals involved. To facilitate this, efficient communications techniques must be applied along with excellent management skills. Below are some of the necessary communications strengths.

Communications Strengths of Leadership Team

- Develops a common vision
- Develops a common data base and terminology
- Establishes the grand scheme of the space elevator [Deployment phase leading to the Wright-Flyer and finally to the Mature industry]
- Segments the project to ensure each part is achievable
- Defines a top level schedule that shows the full project
- Estimates costs of the mega-project to ensure a common commitment

3.4.2.3 Guideline # 3 "Architectures should be relatable, compatible and integratable across mission areas." Architectures must be understood by all who are working on the project and all who are stakeholders in its final success. To achieve this task, the architecture must be presented in terms that each set of teams will understand. Some key elements are noted below.

Key Elements for Consistency

- Continually re-enforce space elevator benefits
- Develop marketing plan for support from space faring nations
- Continually show how the project fits together by relating the major segments as well as the white spaces between each
- Develop an understanding of all of the segment interface relationships such as operating approaches for climbers on the ribbon
- Ensure that everyone understands the threats to the project and associated risks

3.4.2.4 Guideline #4 "Architectures should be modular, decomposable and reusable." This is an easy one to conceptualize, but much harder to implement. Most contractors and players in the development of an embryonic concept want to create concepts for themselves and ensure that their design is the chosen one. However, if a project of this size is to be successfully completed, standards and reusability must be implemented across the segments. As a result, the space elevator is divided into three development phases (deployment, Wright-Flyer, mature) and identifiable segments with time phases. The major space elevator segments are listed below.

Major Space Elevator Segments

Deployment Spacecraft
Command & Control
Anchor Infrastructure
Power
Climbers
Integration Facilities
Ribbon
Tracking Station
Fabrication facilities
Safety Infrastructure

3.4.3 Interrelationship of Views Figure 3-5 shows the interrelationship between the three architectural views. A careful look at these components will show that the big picture can be assessed from parts.

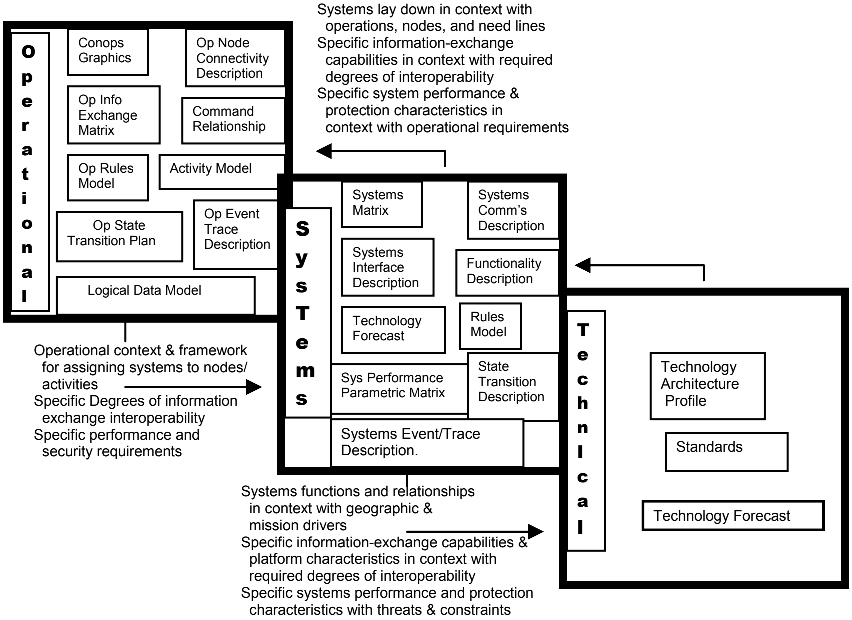

Figure 3.5, Interrelationship Among Architecture Views and Products[54]

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[54] Adapted from *DoD Architecture Framework*, Version 1.0, 30 August 2003

3.4.4 Six-Step Process[55]

The process of developing an architecture is laid out in six steps. Figure 3.6 shows the process steps while Table 3-3 expands upon the process.

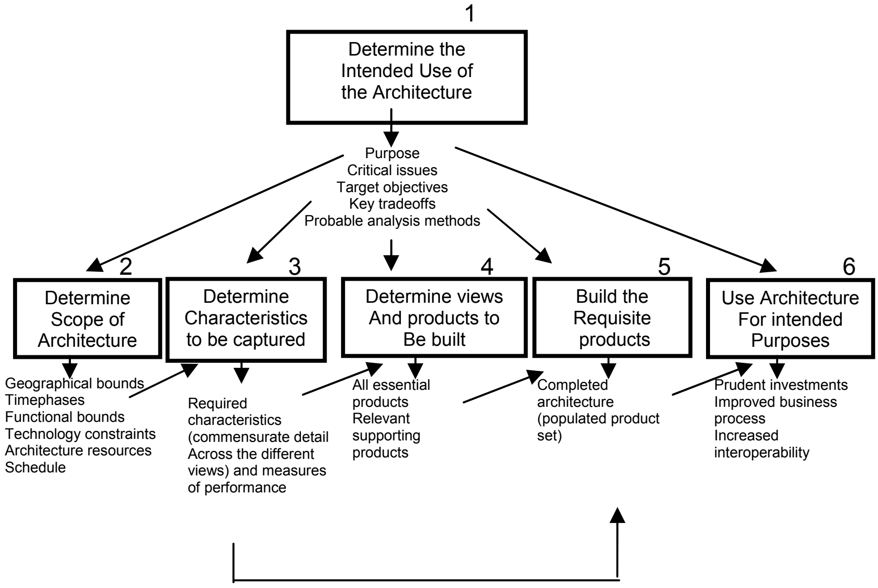

Figure 3.6 Architecture Process[56]

3.4.5 Six Step Process Applied to the Space Elevator

The development of a multi-dimensional architecture is a complex process and must be undertaken with a sense of discipline. Guidelines (see section 3.4.1) combined with a set of processes should enable the designer, systems engineer and systems architect to incrementally proceed. The following six steps provide a good starting point for this Wright-Flyer project.

3.4.5.1 Step 1 – "Determine Intended Use of the Space Elevator" It turns out that the principle motivator for the team is the belief that they are contributing to an exciting project that will open up space commerce. Indeed, the space elevator will have great power as a motivator as it

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[55] Ibid.

[56] Adapted from *DoD Architecture Framework*, Version 1.0, 30 August 2003.

will greatly change the way the world looks at space and our ability to get there.

Table 3-6, Six Step Architectural Process[57]

Step	Explanation
1 - Determine the intended use of the architecture	In most cases, there will not be enough time, money, or resources to build top-down, all-inclusive architectures. These should be built with a specific purpose, whether the intent is business process reengineering, system acquisition, system-of-systems migration or integration, user training, interoperability evaluation, or any other intent. Before beginning to describe an architecture, an organization must determine, as specifically as possible, the issues the architecture is intended to explore, the questions the architecture is expected to help answer and the interests and perspectives of the audience and users.
2 - Determine architectural scope, context, environment and any other assumptions to be considered	Once the purpose or use has been decided, the prospective content of the architecture can be determined. Items to be considered include, but are not limited to, the scope of the architecture (activities, functions, organizations, timeframes, etc.); the appropriate level of detail to be captured; the architecture effort's context within the "bigger picture," operational scenarios, situations and geographical areas to be considered; the projected economic situation and the projected availability and capabilities of specific technologies during the timeframe to be depicted. Project management factors that contribute to the above determinations include the resources available for building the architecture as well as the resources and level of expertise available for analyzing the architecture.
3 - Based upon the intended use and the scope, determine characteristics	Care should be taken to determine which architecture characteristics will need to be described to satisfy the purpose of the architecture. If pertinent characteristics are omitted, the architecture may not be useful; if unnecessary characteristics are included, the architecture effort may prove infeasible given the time and resources available, or the architecture may be confusing and/or cluttered with details that are superfluous to the issues at hand. Care should be taken as well to predict the future uses of the architecture so that, within resource limitations, the architecture can be structured to accommodate future tailoring, extension, or reuse.

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[57] Adapted from *DoD Architecture Framework,* Version 1.0, 30 August 2003

4 - Based upon characteristics displayed, determine AVs	Depending upon steps one through three, it may not be necessary to build the complete set of architecture views and supporting products. Beyond the essential products that must be built for all architectures, only those supporting products that portray the required characteristics should be built.
5 - Build the requisite product	The obvious next step is to build the required set of architecture products, which consist of the essential products, the needed supporting products, and individually-defined products driven by architecture specific needs. To facilitate integration with other architectures, it is critical to include all depictions of relationships with applicable mission components. If the architecture needs some re-tailoring to serve its purpose, that tailoring should be done as efficiently as possible. In this regard, it may be useful, resources permitting, to conduct some proof-of-principle analyses of the architecture at various stages of its development, ie., make trial runs of step six using carefully selected subsets of the areas to be analyzed. Care should be taken to ensure that the products built are consistent and properly interrelated.
6 - Use the architecture for its intended purpose	Architecture will have been built with a particular purpose in mind. As stated in the discussion of step one, the ultimate purpose may be to redesign operational processes, to consolidate and streamline systems, to provide documentation for training personnel, to support the need for proposed systems, or some other purpose. It must be emphasized that the architecture facilitates and enables these purposes but does not itself provide conclusions or answers. For that, human and possibly automated analysis must be applied. The architectural framework does not attempt to dictate how this analysis should be performed rather, the framework intends to promote architectures that are sufficiently complete, understandable, and integratable to serve as a basis for such analysis.

Paradigms will not only change with respect to big boosters on launch pads, but will change things like how to design a satellite (without any rock and roll of liftoff, as a starter), tourism in space, and lunar exploration. Therefore, the following table shows the intended use of the space elevator, and a short description of community benefit.

Table 3.7, Usage and Benefits

Intended Usage	Benefit to Community
Low cost to space	Tremendous savings ($100 per kilogram to GEO altitude) enabling wider access
Easy Launch within Solar System	Tremendous leverage providing velocity through centrifugal launch without chemicals
Human Presence	Humans provide great strengths (100 km hotel, GEO work station, & lunar base)
New avenues for space access	Entrepreneurial activities will spring up to use this cheap access to altitude
New avenues for design systems	Without the stress requirements of big boosters and with the ability to assemble on orbit, new designs will surface
Transportation enabler	Interstate highway infrastructure development established and nurtured new businesses

At this point in the discussion critical issues should surface to ensure that the initiation of a space elevator project is achievable. Some of the critical issues that are facing this mega-project are shown in the following list.

Critical Issues

- Materials development, manufacturing and schedule
- Sponsorship for the project; international, US, NASA, DOT, private?
- Funding needs; when, how much, what form, how provided
- Schedule for the mega-project
- Engineering trades identification
- Ribbon manufacturing

- Ribbon design
- Survival of space elevator system
- Base station location and options
- Power to altitude (propulsion choices)

Another item that must be identified early in the conceptualization process is the set of initial goals. If the team does not start out with a set of initial goals, they will never know when they are successful. Here are a set of goals that could motivate the space elevator to kick off as a project.

<u>Goals</u>

- Partnership Funding created by 09/2006
- Funding Approval by 06/2007
- Segment Preliminary Design Reviews during 01-07/2009
- System Critical Design Review by 01/2010
- Ribbon deployment from GEO by 01/2017
- Wright-Flyer sends first customer (paying satellite) to altitude by 01/2016

3.4.5.2 Step 2 – "Determine the Scope of the Architecture"

There are many aspects to determining the scope of a mega-project. Some of the scope issues are noted below.

<u>Scope of Project</u>

- Global reach of the partnership
- Number of space elevators in the Wright-Flyer Infrastructure
- Location of base station
- Phases of the program

  Team forming 06/2003 - 01/2006

  Deployment Phase

Design, manufacturing	1/2006 - 01/2010
Ribbon Deployed	by 01/2014
Wright-Flyer Phase	
Ribbon build-up by climbers	01/2014-01/2017
First customer	01/2017
Second parallel Elevator	01/2018
Full System Phase	
First human ride	01/2020

Included in this early consideration is the concern for boundaries. Where can the space elevator team maneuver? How much leverage does the team have? One of the big questions in this project will be the issue of whether the space elevator will be government sponsored, government funded, and/or government executed? A completely private operation will require permission to go ahead and will need to work closely with the governments around the world. Funding is a big issue. Who will fund the space elevator? What model will be used to structure the funding profile? Big Government? Interstate highway development approach? Big budget approach? Private investment? Bridge building approach?

Another key item that must be understood is the need for resources. The estimated price of a Wright-Flyer operation has been quoted between $6 and 12 billion. If it is to be a commercial project, the profitability and return on investment must happen relatively quickly. In addition, there are many other resources required, such as: regulation waivers, government approvals, land usage, Law of the Ocean modification, and, of course, the human capital of inventions, creation, manufacturing and assembly.

3.4.5.3 Step 3 – "Determine Characteristics to be Captured"

The key characteristic to ensure satisfaction of customers is the representation of the space elevator as an elevator. Each of us has an understanding of that word, usually presupposing:

SAFE – TIMELY – INEXPENSIVE

However, it must be recognized that the critical human response to the word elevator is ***Safe***. Other words that come to mind when discussing an elevator include:

LOGISTICALLY SOUND, DUAL DIRECTIONAL,
and COMFORTABLE

Another key characteristic that needs to be recognized for the space elevator is that the environment of space is dangerous, and, with small mistakes, even deadly or catastrophic. As a result, the design, development, and operations of a space elevator must include tremendous efforts to provide logistics integrity, reliability and survivability for both robotic and human cargo.

Measures of performance for a space elevator will boil down to two key measures: profitability and safety. No one will care in the long run if the logistics climber takes three weeks to arrive at the lunar launch station, vs. 2 weeks, if the safety and profitability are meeting expectations.

3.4.5.4 Step 4 – "Determine Views and Products to be Built"

For the full development of the space elevator with all three phases (deployment, Wright-Flyer, and Mature), the product list of architectures is shown in Table 3.1. However, this chapter is just looking at the initial product, AV-1, Overview and Summary Information. This AV-1 is developed in Section 3.5 with a good representation of where the project is going.

3.4.5.5 Step 5 – "Build the Required Products"

The list was shown in Table 3.1 and each will be developed as the space elevator program progresses.

3.4.5.6 Step 6 – "Use Architectures for Intended Purposes"

The purpose of the next section (3.5) is to show a top level Architectural view. This is presented with the focus on the Wright-Flyer to enable the community to initiate a mega-project. The AV-1, Overview and Summary Information, is to establish the baseline concept and kickoff the development of the other architectural views.

3.4.6 Architectural Tools The tools to complete a systems architecture for the space elevator largely exist in the commercial environment. Their primary role is to help in the management of all the phases of development, production, and operations. The architectural tools are broken out as shown next.[58]

- Architecture modeling tools
- Architecture repository tools
- Customization to support user needs and environments
- Interoperability tools
- General characterizes of the tools for cross programmatic use
- Vendor characteristics fall out as they are exercised

3.5 Space Elevator Architecture View-1 (AV-1)

This preliminary product of the Wright-Flyer space elevator will represent the starting point for development of all the Architectural Views required for kicking off a project of this magnitude. One key is that this development of the ”Overview and Summary Information” (AV-1) will enable the project team to initiate activities appropriate for the creative and innovative phase of the design. The purpose is to show the value of the systems architectural process and formulate an initial set of conditions for the development team. As modeled in Table 3.8, the following section illustrates a representative format.

3.5.1 AV-1: Overview and Summary Information AV-1 is intended to document the assumptions, constraints, starting point, and limitations for the development of the Wright-Flyer space elevator. The basic question required to achieve initial funding falls into AV-1. The Overview and Summary Information architectural view should have the funding sources identified, a baseline schedule laid out and an authority to proceed.

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[58] *DoD Architecture Framework*, Version 1.0: pg 6-6, 2003.

Table 3.8, AV-1 Overview and Summary Information[59]

Architecture Project Identification

- *Name*
- *Architect*
- *Organization Developing the Architecture*
- *Assumptions and Constraints*
- *Approval Authority*
- *Date Completed*
- *Level of Effort and Projected and Actual Costs to Develop*

Scope: Architecture View(s) and Products Identification

- *Views and Products Developed*
- *Time Frames Addressed*
- *Organizations Involved*

Purpose and Viewpoint

- *Purpose, Analysis, Questions to be Answered by Analysis of Architecture*
- *Viewpoint from which the Architecture is Developed*
- *Context*
- *Mission*
- *Doctrine, Goals, and Vision*
- *Rules, Criteria, and Conventions Followed*
- *Tasking for Architecture Project and Linkages to Other Architectures*

Tools and File Formats Used

TBD

Findings

- *Analysis Results*
- *Recommendations*

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[59] Adapted from *DoD Architecture Framework*, Version 1.0, 30 August 2003

Wright-Flyer Space Elevator Preliminary Architecture View 1 (AV-1) Overview and Summary Information

Architecture Project Identification

Name : Wright-Flyer Space Elevator - During the development of a mega-project, multiple phases must be laid out to ensure progress is made using an incremental approach. Engineering processes need to build upon solid bases in manageable steps. As a result, this book has divided the development of the space elevator into three phases: Deployment, Wright-Flyer, and Mature, and is focused on the first and second phases.

Architects: John Smith
Chief Architect
Space Elevator, Inc.

Organization Developing the Architecture: The lead for the Wright-Flyer space elevator concept is….(TBD). There are also many principal players in the project, especially from Los Alamos National Laboratory and NASA.

Assumptions and Constraints: General constraints include: 1) a budget that does not exceed that affordable by NASA, private investment or DoD., 2) risk levels that allow for a safe operation, and 3) a schedule that represents substantial progress toward completion.

Approval Authority: The approval authority will most likely reside within the funding go-ahead organization. The rules, regulations and laws that lead toward final authority to start construction reach across the globe and touch local, national and international communities.

Date Completed: Major steps along the way are:

- Partnership Funding created by 09/2006
- Funding Approval by 06/2007
- Segment Preliminary Design Reviews during 01-06/2009

- System Critical Design Review by 01/2010
- Ribbon deployment from GEO by 01/2014
- Wright-Flyer sends first customer (paying satellite) to altitude by 01/2017

Level of Effort and Projected Actual Costs to Develop the Wright-Flyer: The estimate for a space elevator program is just that, and estimate. A lot of work must be accomplished to use a new technology across a hazardous environment. The cost estimates below were given at the 2nd Annual International Conference on the space elevator and presented in the Edwards book.

Table 3.9. Cost Estimates[60]

Component	Cost Estimate
Launch costs to GEO	$1.02B
Cable production	$390M(100% contingency)
Spacecraft	$507M(100% contingency)
Climbers	$367M
Power beaming stations	$1.5B
Anchor station	$120M
Tracking facility	$500M
Other	$430M
Contingency (30%)	$1.44B
TOTAL	~$ 6.2B

The assumptions that went into this estimation are based upon the following.

1. Launch costs to GEO: 4 expendables ($270M each)
2. Ribbon production: $100/kg for carbon nanotubes, interconnect production, fabrication facility construction and operation, 100 % contingency.
3. Spacecraft: Broken down to component level (photocells, control, structures, propulsion), 100% contingency.

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[60] Edwards, Bradley C. & Eric A. Westling, *The Space Elevator*, BC Edwards, Houston, TX, 2003.

4. Climbers: Broken down to component level (photocells, motors, treads, control, structure) replication cost savings assumed
5. Power beaming station: 3 stations (two ocean, one land) based on Bennett Optical design estimates
6. Anchor station: based on information from existing systems, Art Anderson Associates and Hyundai
7. Tracking facility: NASA study, Allen One Hectare telescope
8. Other: assembly, development and administrative costs
9. Miscellaneous and contingencies approximately 30 %

Scope: Architecture View(s) and Products Identification

Views and Products Developed: The AV-1 for a Wright-Flyer is presented with recognition that a majority of the remaining architectural views would be completed by the start of project funding for the space elevator. The space elevator mega-project will be segmented during the process of development to ensure the spread of responsibilities leading to approaches based upon work breakdown structures. To fully understand the product segmentation of the space elevator, the following paragraphs describe each briefly. This set of segments illustrates the breadth and level of complexity inherent in a project of this magnitude. The segmentation is also presented within the three phase process (deployment, Wright-Flyer, and Mature space elevator).

***Deployment Phase Segmentation*:** Breakout of a mega-project is always complex and requires imagination and "big picture" visualization to ensure all aspects are reflected early in the design process. As complexity provides a type of fog to this visualization, segmentation helps significantly. For the deployment phase, the following segments set the stage for development.

Launch: Large launch vehicles will be required to lift the deployment spacecraft and place it into orbit. Currently, the estimate is that available launch vehicles can handle the task. This would include, but not be limited to: Ariane, Boeing's Delta IV, Lockheed Martin's Atlas V, and the Proton. However, as all good space systems engineers know; spacecraft increase in mass as you approach reality. The added complexity of multiple launches (the current design calls for four) and assembly on orbit is not significant as the spacecraft assembly is a simple bolting together of the components without critical alignments. The deployment spacecraft will be assembled at low Earth orbit (LEO).

Deployment Spacecraft[61]: The deployment spacecraft will consist of all housekeeping aspects such as heating, cooling, power, attitude control, command and control, communications, and propulsion. The payload of this spacecraft would in essence be two spools of ribbon for deployment. After deployment of the 100,000 km ribbon, the spacecraft would remain permanently attached to the end of the ribbon as the first component of the counterweight. The scenarios for the spacecraft would be: design, assembly, mating with rocket, launch, assembly at LEO, electric propulsion or rocket delivery to equatorial GEO, checkout of mission components, deployment of the ribbon down toward Earth, stability control during deployment, velocity control of the ribbon, and anchoring the end of the ribbon at completion. Related aspects of the operation are ensuring the lower end successfully arrives at Earth at a controlled velocity, is found by the anchor and securely attached. All of these activities must be completed on a precise schedule.

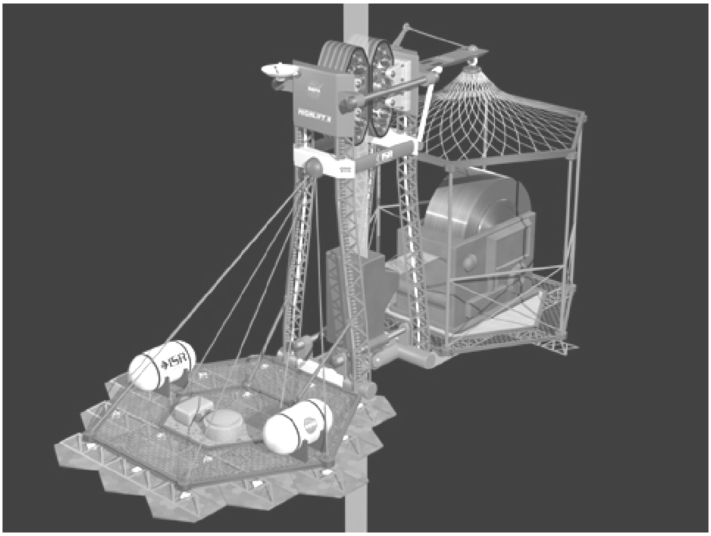

Figure 3.7, Spacecraft Concept[62]

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[61] This assumes a single spacecraft during the deployment phase, but it is not hard to extrapolate to assembly steps of multiple spacecraft being put together at LEO.

[62] Figure used with permission of the Institute of Scientific Research, Inc.

Deployment Spool: The deployment mechanism for the ribbon will be designed around the principle of simplicity. The starting point will be similar to a deep sea fishing reel with a mechanism to spool across its width and smoothly reel out the ribbon. Initial control, first kilometer, of the ribbon will be handled by a set of small gas jets on the ribbon end weight. Once the ribbon has deployed to a certain distance, the dynamics will be predicable and the speed will need to increase to a reasonably high rate since 100,000 km is a long way to "lay a cable." The process for the spool mechanism is: design, develop, test – test - test, assemble for flight, checkout on spacecraft, launch to GEO, initiate ribbon deployment, control release, and finalize stability after anchor.

Ribbon on Spool: The development of nano-technology is progressing at a remarkable rate with promises of tremendous explosive growth in certain areas. One area of significant advancement is the growth of "nanotubes" to lengths compatible for building the space elevator. The motivation for technological development is the phenomenal number of uses for lightweight, strong materials in everyday life. The growth of this technology will enable space elevators and is being planned for by the engineering team. As a result, the concept of the space elevator is one meter wide ribbon composed of fibers 10 to 50 microns in diameter. This phenomenally light and extraordinarily strong material will ensure a robust space elevator. There is a tremendous amount of research, analysis and development work being conducted on this topic and progress toward the strength required for the space elevator is rapid.

Counterweight: When the ribbon for the space elevator reaches from beyond GEO altitude to the surface of the Earth, it requires a substantial counterweight to balance the downward pull of gravity on the lower end. A balanced system minimizes the mass and complexity of operation of the space elevator. One method would be to just run a long ribbon until it is balanced, though this is not optimal from a systems engineering standpoint. Mass in the form of the spacecraft and construction climbers are available and to not use them when it is so simple would be a poor design choice. Another more creative approach would be to collect old GEO spacecraft for free mass. As they are parked about 100 km above the GEO altitude, and have an orbital velocity less than GEO satellites, they will slowly pass the space elevator corridor. This would enable them to be "plucked" with minimum complexity and added to the space elevator counterweight.

Command and Control: This segment will have a major role in the orderly assembly of a Wright-Flyer. As a result, many methods, techniques, and types of equipment will evolve. The basic concept is that segments of the space elevator will be connected for communications with at least three components; computer for control, communication devices (laser or radio frequency), and GPS location devices. This ensures diversified computing and communications enabling a phenomenally complex deployment to be achieved. One strength of this deployment approach is that most of the operations will be conducted inside the space elevator corridor directly above, and in line-of-sight with the command and control facility.

Anchor Locations: The location of the anchor has many variables and will be discussed in Chapter 6.

Debris Mitigation Segment: During ribbon design and deployment phase, the team must initiate and execute debris mitigation efforts warranted for the safety of the Wright-Flyer. This would include spacecraft to chase down large objects (rocket bodies, de-activated spacecraft) and de-orbit them. Active avoidance will be used to avoid the remaining debris.

Other Supporting Documents: During the Deployment Phase, there are many activities that require support. Much of that would come from supporting documents setting the stage for the space elevator. Some would be: communications requirements, interface specifications, segment evolution plans, system matrix (information based), systems performance matrix, physical data model, event occurrences, and training and certification.

Wright-Flyer Segmentation: During this phase of space elevator development, essential steps to complete the assembly will be conducted. The first ribbon deployed in the Deployment Phase will not be sufficient to handle the main mission of the space elevator: economical movement of items and people to and from space. The following breakout helps to explain this phase and its segments.

Command and Control Segment: In addition to keeping in touch with all elements of the space elevator, the control center must schedule the interaction of multiple segments and developmental teams. Scheduling, planning, safety monitoring, and inspections will ensure a robust command and control segment.

Construction Climbers: After the space elevator basic ribbon has been anchored to provide the transition from space system to just a high tower or bridge, reinforcement and construction must begin. The initial climber going up will be the "construction climber" that enhances the ribbon in breadth, strength and safety. An estimate is that over 200 runs with construction climbers will be required to manufacture a space elevator with the performance required.

Safety Inspections: Climbers will have sensors to inspect the ribbon at high velocities. The purpose is to do routine inspections during construction or routine deployment. When anomalies are observed they are documented and a specialized repair climber is dispatched to conduct repairs. As with painting the Golden Gate Bridge, repairs on the elevator may be a continuous process.

Climber Segments: The development of climbers will be complex and an integral part of the ribbon design. Each climber must be able to ascend, descend, stop and maintain location on the ribbon. There will be several types of climbers, such as: construction climber, repair climber, general cargo climbers, and human-rated climbers. The climbers will probably have a standard interface with the ribbon, a standard communications node with GPS capability, and unique mission components. The climbers must be designed early to ensure compatibility with the design of the ribbon. Climber power options cover the spectrum from solar to laser to RF to atomic.

Nodal Segment: The development of the stationary (maybe movable, but placed at locations along the space elevator) nodes will be dependent upon the requirements stated at the beginning of development. Some of the concepts for stationary nodes being discussed now are: GEO altitude logistics node, Lunar release point, Mars and beyond release point, and Earth Orbit release point (> 23,700 km).

Power Segment: Powering the climbers could take several forms: conductive for the first 10's to 100 km, laser power beaming up to GEO, solar for some climbers, and power dumping beyond GEO.

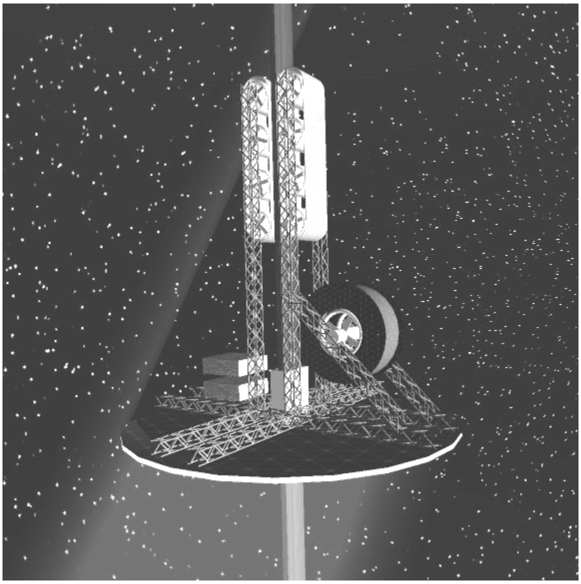

Figure 3.8, A Power Concept – Laser Beam[63]

Safety Infrastructure Segment: This segment will stretch across the full spectrum of this phase of development. In addition, it will leverage activities of the deployment phase and establish patterns for the next phase. Many activities fall under this segment of development including:

Debris Mitigation**:** Initiated early in the developmental phase, but required to increase and be more thorough.

Ribbon Movement Infrastructure: As the operations are started, the ability to move the space elevator out of the path of a large space object becomes an imperative.

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[63] Edwards, Bradley, from work at Institute for Scientific Research, Inc. 2003.

Equipment reliability, protection from human interference, atmospheric influence mitigation such as lightening and winds, are all part of the safety segment.

Other Supporting Documents: During the Wright-Flyer Phase, there are many activities that require supporting information. Some would be: communications requirements, interface specifications, segment evolution plans, system matrix (information based), systems performance matrix, physical data model, event occurrences, and training and certification.

Mature Space Elevator Phase: This third phase of the development will be started with the first human cargo (probably a worker or inspector) and grow exponentially as entrepreneurs develop new and inventive uses for this new access to space. Multiple ideas surface about space elevators placed around the globe, such as logistically managed space elevators side by side to enable continuous flow up one and down the other. However, this AV-1 concentrates on the third phase as one that goes from first human rider to a robust commercial success (still one space elevator). The major segments of the third phase are as follows:

Ribbon Segment: By now the ribbon will be robust and with a human rating. During this robust phase of development people will relate to their known modes of transportation, such as bridges and railroads. The ideas range from multiple strands to side tracks for passing climbers and higher speeds.

Climber Segment: During this phase, the climbers would be more robust and some designs would be human rated.

Command and Control Segment: This vital element of the design will be transformed into an operations center scheduling, planning, billing, ensuring safety, repairing, and enhancing the space elevator.

Other Supporting Documents: to be determined

Time Frames Addressed:

- Partnership created by 09/2006
- Funding Approval by 06/2007
- Segment Preliminary Design Reviews during 01-06/2009
- System Critical Design Review by 01/2010
- Ribbon deployment from GEO by 01/2014
- Wright-Flyer sends first customer (paying satellite) to altitude by 01/2017

Organizations Involved: Many organizations are involved with space elevator research. The scenario for development and construction of the space elevator is yet undecided and could be public or private, a single lead or international collaboration.

Purpose and Viewpoint

Purpose, Analysis, Questions to be Answered by Analysis of the Architecture: The principle driver for the development of a space elevator is "cheap access to space." Many studies have been accomplished on this topic with the realization that $100 / kilogram would be a viable "reach-out" target price.

Viewpoint from which the Architecture is Developed:The development of AV-1 will be accomplished from the team that is involved in the creative process prior to any sizable funding.

Context: The purpose of this AV-1 is to set the stage for the total effort to deploy a space elevator within the next 12 years.

Mission: The mission statement for this mega-project team should be:

Mission Statement: To conceive, gain funding, design and execute development of a Wright-Flyer Space Elevator for a paying customer by 2016.

Doctrine, Goals, and Vision

Space Elevator Vision

The space elevator gives us the road to limitless opportunities while opening up the solar system.

Goals: There are four preliminary goals that support the development of the Wright-Flyer:

- To have the first paying customer by 2017
- To have the deployment phase completed by 2014
- To have the international project funded and sponsored robustly
- To have the ability to lift over 100 13-ton payloads per year

Rules, Criteria, and Conventions Followed: The technical architectural views provide guidelines for the engineers, designers, manufacturers, and assemblers to pull together a mega-project while ensuring segments fit together and systems work compatibly. Early in the developmental process, the systems architect has to ensure that standards are set, conventions are identified (and mandated), rules established, and criteria established that ensure interfaces work and operations succeed. Some of the following items must be integrated into the planning.

Enterprise Wide Standards: To ensure the vision for a project can be successful, enterprise wide standards must be implemented. Design rules must be established across the design and manufacturing teams. Two standards that come to mind are an internet based approach of an open information architecture and the standards of the governing body for space communications, the International Telecommunications Union (ITU).

Internet Standards: Most future architectures want to take advantage of the digital world and its flexibility. Open standards ensure a full spectrum of equipment suppliers will be compatible. As a result, the space elevator enterprise should mandate an internet protocol estimated for its implementation date. A current estimate is that of Internet Protocol, Version 6. Another very important aspect of business is to support the patent process and protection of cross-fertilization of ideas.

International Telecommunications Union Compatibility: The process is already established for gaining communications capability approval for a GEO location. The ITU ensures equality in communications and allocates for the GEO arc around the Earth. As a result, the space elevator enterprise must chose a frequency and proceed to gain approval for not only GEO, but the whole space elevator corridor. The team should pursue both RF and laser communications capabilities.

Manufacturing processes: For a project of this magnitude with a requirement that the ribbon have no material flaws across the full deployment, a major quality requirement must be established early. The standard for most American manufactures is around six sigma, or no more than 3.4 errors in a million operations. Many manufacturers are reaching the phenomenal goal of nine sigma (or 10s of errors per billion operations). This achievable number is what ribbon manufacturing may need to standardize upon during production.

Survivability Levels: As a major transportation node to space, the space elevator has a "no sever" requirement. Chapter 5 discusses this arena and establishes that the goal of "no sever" can be achieved with the proper design.

Interoperability: One key to mega-project development is the ability to "plug and play" with various segments and components. This is essentially a basic requirement on the space elevator design: "Any climber that meets a set of design standards can ride the ribbon!"

Tasking for Architecture Project and Linkages to Other Architectures: In addition to the obvious communications interoperability, all of the physical connectivity must be ensured. A standard (similar to railroad interface standards) must be established so all suppliers may traverse the space elevator in a safe and timely mode. As the space elevator is essentially a straight line from the equator to the counterweight 100,000 km above the base station, connectivity will be by laser (and RF) communications devices located throughout the project. The strengths of laser communications are that the equipment is small, robust and transmits large quantities of data. The interoperability of all the segments is critical for safety and survival of the space elevator as well as the day to day operations.

Tools and File Format Used: The tools and file format for the project are to be determined (TBD) at a later date.

Findings:

There are many items that fit into this section. Some are:

Rules of the Road: tbd

Logistical Plan: To be developed after a program plan is developed and a schedule of events is established.

Concepts of Operations: The development of a concept of operations is a taxing process that lays out the approach to handle the day to day activities of the space elevator. The AV-1 does accomplish this, but some elements for a space elevator Concept of Operations are:

(a) Segment communication infrastructure

(b) Location of ground operations

Staffing and Responsibilities: To be developed after the core development team has been established.

Survivability Policy: To be developed later, however, as this is a major concern for the space elevator, risk management issues are expanded upon in Chapter 7.

Security Plan: tbd

Activity Model and Event Types: During the operations of the space elevator, there will be many general concepts. A few are:

> Space Elevator Construction: This will consist of a climber that uncoils a new piece of the ribbon as it ascends. The approach to the splicing and the cross strapping will be finalized during material selection and design development (multiple trips – approximately 200 times).
>
> Space Elevator Repair Climber: This climber will routinely repair smaller rips and tears from operations, orbital debris, and micrometeorites.
>
> Cargo Delivery Climber: This is the mainline business vehicle to move cargo. The current goal is 13 tons of cargo and 7 tons of climber.
>
> Power Generation: This energy source (ground based or space based) would provide laser power to the multiple climbers on the ribbon.

Analysis Results: Some obvious results have already been observed:

- Materials development is "long pole in tent"
- Revolutionary savings result from a Wright-Flyer
- The world of space will change after the Wright-Flyer

Recommendation from Architectural View #1:

Proceed with Wright-Flyer

Space Elevator Development!

CHAPTER IV – SYSTEMS ENGINEERING APPROACH

4.0 Systems Engineering Overview[64]

This chapter presents an overview of the systems engineering process and how it applies to a space elevator. Included in this explanation are identification of engineering trade spaces, critical programmatic issues and vital concerns for the space elevator project. The question of "Why systems engineering?" is asked, but more and more the successes of mega-projects using the process has quieted the detractors. The systems engineering mission is to "Assure the fully integrated development and realization of products which meet stakeholders' expectations within cost, schedule and risk constraints." [65] The bottom line is that when the approach is properly applied to the systems-of-systems project, systems engineering will:

- Provide a structured process for integrating and linking requirements, schedule, decision milestones, and verification;
- Enable the project team to work to an integrated set of requirements and processes;
- Enable integration of the system at the requirements and design stages (before sunk costs) rather than waiting until hardware and software is available;
- Reduce unplanned and costly reengineering necessary to resolve omissions and integration difficulties.

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[64] Much of this chapter covering the description of systems engineering was taken from the website from SEPrimerAIAA-INCOSE_1997-08.

[65] SEPrimerAIAA-INCOSE_1997-08, p 3.

The chief systems engineer of a mega-project is responsible for the integrity of the systems engineering process, which has been defined as:

> ….. the ***systems engineering process*** is basically an iterative process of technical management, acquisition and supply, system design, product realization, and technical evaluation at each level of the system, beginning at the top (the system level) and propagating those processes through a series of steps which eventually lead to a preferred system solution. At each successive level there are supporting, lower-level design iterations which are necessary to gain confidence for the decisions taken.[66]

The following items will be expanded upon in this chapter to ensure an understanding of the complexity of systems engineering issues and how they play within a mega-project such as a space elevator:

4.1 Systems engineering process

4.2 Systems engineering process tasks

4.3 Hierarchical levels approach

4.4 Space elevator development approach

4.5 Why pursue a space elevator – the Motivation

4.6 The spectrum of trade spaces as applied to Wright-Flyer

4.7 Systems engineering concerns – interfaces/requirements

4.8 Setting the stage for the next two chapters (Space Elevator Survivability and Base Leg Alternatives)

4.1 Systems Engineering Process

Systems engineering brings two vital elements to a project that are not usually present:

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[66] *Systems Engineering Handbook,* INCOSE, Version 2.0, July 2000, pg. 16.

- A disciplined focus on the end product, its enabling products, and its internal and external operational environment (i.e., a system view)
- A disciplined vision of stakeholders' expectations independent of daily project demands

The definition of systems engineering for major mega-projects within the US Department of Defense is:

> The application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into total engineering effort <u>to meet cost, schedule, supportability and technical performance objectives</u>.[67]

The systems engineering process[68] concept has been defined by INCOSE (International Council on Systems Engineering) as–

- Plan and organize the technical aspects of the project
- Analyze the problem posed by the stakeholders
- Define the stakeholders' problem by converting needs and expectations into validated and integrated technical requirements
- Develop detailed technical requirements to the extent necessary to enable feasible and economical design solutions
- Assess and evaluate alternatives which may satisfy these needs and expectations and select a balanced solution for each system element as well as a balanced solution for the system as a whole

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[67] "Conducting Program Reviews," briefing by the Aerospace Corporation, 2001.

[68] SEPrimerAIAA-INCOSE 1997, p. 3.

- Ensure implementation of the balanced solution (design the end product)
- Verify the solution satisfies the stakeholders' requirements

This process depends on systems architecture setting the stage, program management supporting the programmatics robustly, and systems engineering executing the following: requirements management, risk management, and technical reviews. The elements of success for systems engineering depend upon:

- Organizations need to understand that systems engineering is as much a way of thinking and doing business as it is a process.
- It requires a firm commitment of all participants – from the most senior member of management to the new hire at his or her workstation.
- Systems engineering doesn't call for an isolated team "doing systems engineering," but rather, it instills an infrastructure in which the organization, the project management team, and team members operate on a daily basis.
- Systems engineering defines how the organization discerns a problem, how it approaches the development of a solution to that problem, and how it implements the plan which enables the problem to be solved.

4.2 Systems Engineering Process Tasks The basic tasks derived from the systems engineering process can be presented as shown in Table 4.1. This table is a tool to help enable this book to assess the Wright Flyer space elevator systems engineering approach and will be used as a baseline in Chapter V (Systems Engineering Trade: Space Elevator Survival) and VI (Systems Engineering Trade: Base Leg Infrastructure).

Table 4.1, Process Tasks

	Systems Engineering Process Task
1	Define the System Objectives (User's Needs)
2	Establish the Functionality (Functional Analysis)
3	Establish Performance Requirements (Requirements Analysis)
4	Evolve Design and Operations Concepts (Architecture Synthesis)
5	Select a Baseline (Through Cost/Benefit Trades)
6	Verify the Baseline Meets Requirements (User's Needs)
7	Iterate the Process through Lower Level Trades (Decomposition)

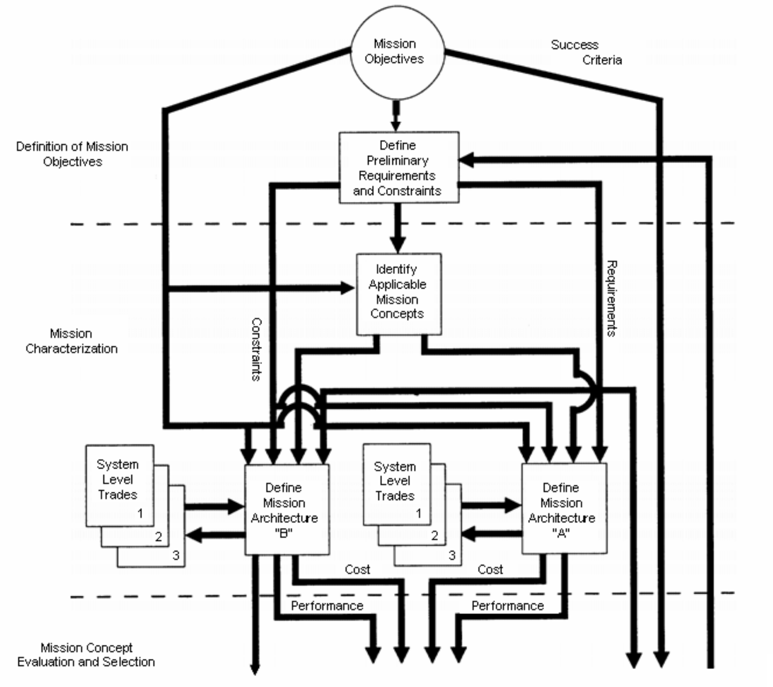

Figure 4.1, Conceptual Steps in Systems Approach[69]

Another way to look at it is the flow diagram that shows the Systems Engineering Design process with trades between alternative concepts (in this case, just two, but could be multiple concepts at this preliminary stage). Figures 4.1 and 4.2 show the flow diagrams for this process.

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[69] Larson, Wiley J. and James R. Wertz, *Space Mission Analysis and Design*, Kluwer Academic Publishers, The Netherlands, 1999, p. 20.

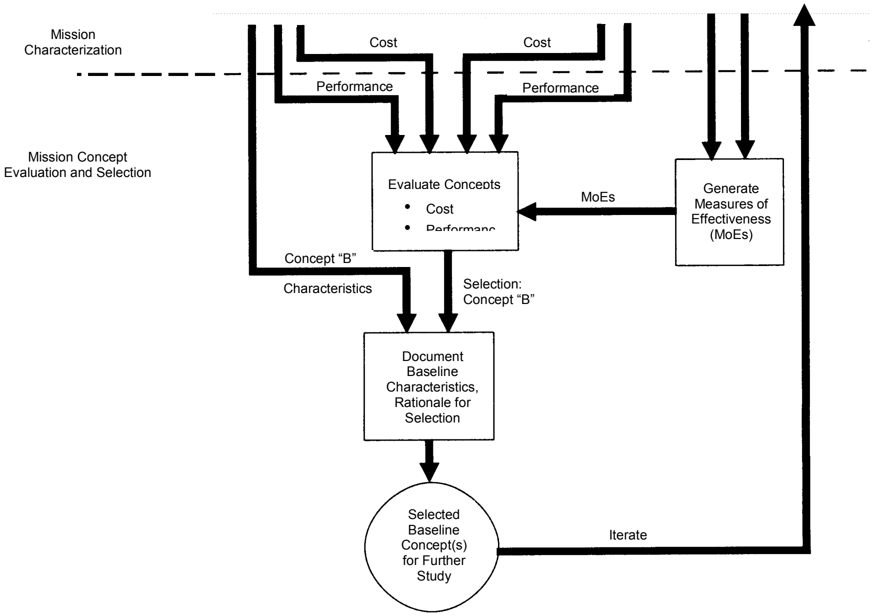

Figure 4.2, Synthesis Steps in Systems Approach[70]

4.2.1 Tools and Documents This set of tasks and processes is in reality continuous with many levels within the management and technical system. Under this structure the chief systems engineer is responsible for the technical arena with technical management and the decision maker when major trade studies result in multiple answers. Some of the items that the chief systems engineer is responsible for are listed in Table 4.2.

Table 4.2, Systems Engineering Tools

Tools
Systems Engineering Management Plan (SEMP)
Organizing using Integrated Process and Product Development Teams (IPPD)
Systems Engineering Master Schedule (SEMS)
Risk Management
Systems Engineering Process Metrics

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[70] Larson, Wiley J. and James R. Wertz, *Space Mission Analysis and Design,* Kluwer Academic Publishers, The Netherlands, 1999, p. 20.

Technical Performance Measurement (TPM)
Roles and Functions of Reviews and Audits
Configuration Management

One dominant key element in the overall engineering plan is the Systems Engineering Management Plan (SEMP) which includes:

Administration – Cover, Title page, Table of Contents, Applicable Documents
Scope
Systems Engineering Process
Transitioning Critical Technologies
Integration of the Systems Engineering Effort
Additional Systems Engineering Activities
Notes and Appendices

The SEMP is the workhorse of the systems engineering tool box. It is a top-level plan for looking at all the aspects of the system and managing the flow of activity. Organization, structure, which engineering principles and processes will be followed, and basic customer requirements will be identified inside the SEMP.

4.2.2 Responsibilities In addition to the SEMP living document, the chief systems engineer has the following major responsibilities.[71]

Requirements Management: The chief systems engineer must ensure a stable set of requirements that can act as a baseline. There must be bi-directional traceability, early identification of inconsistencies, continuous analysis of requirements with respect to systems trades, and a verification path to ensure that all requirements are satisfied.

Modeling and Simulation for Independent Verification and Validation: Rigorous and consistent evaluations must be conducted throughout the lifecycle to enable better engineering and management decisions. Early systems concepts must not only be validated against requirements, but be shown to fulfill lifecycle cost estimates. In addition, modeling and simulation must be used to plan tests and illustrate validation and verification.

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[71] Systems Engineering Briefing, Office of the Under Secretary of the AF, DoD presentation, 2002.

Software Development: The software requirements must be defined early, along with hardware and systems level requirements. Early review of software requirements, models and tools must be accomplished by appropriate technical experts. Matching incremental software builds with the program schedule is a principal need for systems engineering.

Verification and Validation: A rigorous process must be established early to ensure the design team is aware of their responsibilities. Verification ensures deliverables are in compliance with functional, performance and design requirements. Validation is to ensure requirements are consistent and couple with respect to the higher level customer needs. A verification and validation plan is the systems engineer's responsibility to develop, monitor and ensure compliance.

Integration, Test, Launch, and Flight Operations: An integration and test plan must be established early to enable the designers to plan and implement. The V model is the baseline, with pyramidal test philosophy and "end-to-end" testing essential to success.

4.3 Hierarchical Levels Approach

The systems engineer must be able to work across hierarchical levels to ensure that the project is accomplished on time and within budget. This breakdown into the level of assembly of a system is given in the following table. Another view of the breakdown of a system is by the tiering of systems and their relationships within the space elevator, as shown in Figure 4.3. If the systems engineer deals with the requirements and risk management activities, the project should flow smoothly. The principle responsibility is the continuity of technical requirements until the end product is delivered. As systems become more complex, systems engineering tasks become more multi-disciplinary and require excellent communications skills.

Table 4.3, Systems Hierarchy[72]

Systems Engineering Level	**Definition**
System-of-Systems	A series of systems that are integrated to work harmoniously across the environment
System	An integrated set of elements, segments and/or subsystems to accomplish a defined objective.
Element or Segment	A major product, service, or facility of the system, e.g., the aircraft element of an air transportation system (commonly used, but subsystems can be used instead of element/segments).
Subsystem	An integrated set of assemblies which performs a cleanly and clearly separated function, such as communications, electronics, structures, or controls; involving similar technical skills, or possibly a separate supplier.
Assembly	An integrated set of components and/or subassemblies that comprise a defined part of a subsystem, e.g., the fuel injection assembly of the propulsion subsystem.
Subassembly	An integrated set of components and/or parts that comprise a well-defined portion of an assembly.
Component	Comprised of multiple parts; a cleanly identified item.
Part	The lowest level of separately identifiable items.

To execute this responsibility, the systems engineer must be responsible for the trade-off studies that are necessary to progress within a mega-project. The issue is that risk management and technical problems seldom reside within just one portion of the project, they cross many artificial borders, such as segment or assembly definitions. As such, key trade studies are conducted at the systems level to ensure that optimization occurs at the proper level for

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[72] Adapted from *Systems Engineering Handbook*, INCOSE, Version 2.0, July 2000, p. 12.

the project. As the lead for technical understanding, the systems engineer must describe their process and ensure that it is followed throughout the project's life.

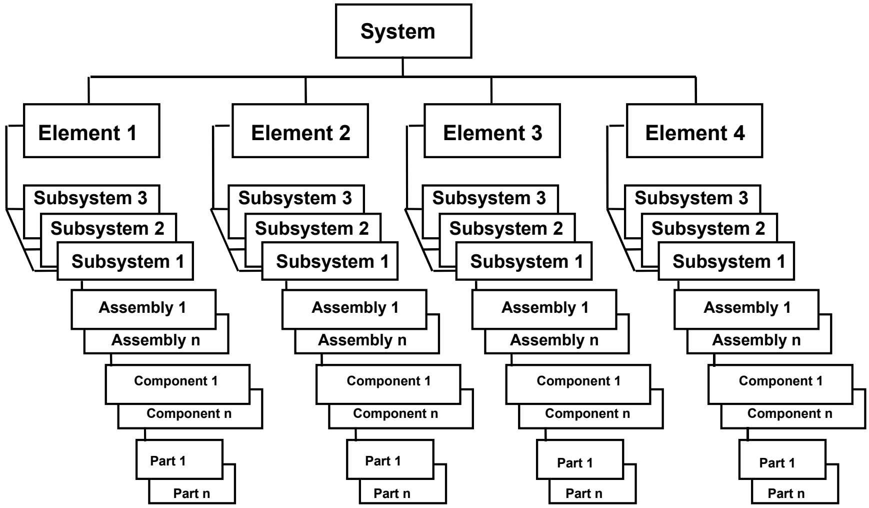

Figure 4.3, Hierarchy of System Elements[73]

4.4 Space Elevator Systems Engineering Approach

4.4.1 Comparison The systems engineering team will initiate the project with many unknowns and many questions. The size and complexity of a space mega-project should be put in perspective to encourage comparisons to successful projects that are as challenging as a space elevator. Table 4.4 shows some interesting comparisons of programs that cost more than a billion dollars and take longer than ten years to complete.

The table lists space, aeronautical, bridge/tunnel, and building mega-projects. They range from slightly under a billion dollars to in excess of $60 B. A good example is the bridge from Denmark to Sweden or the English-French Chunnel.

To accomplish the daunting challenge of constructing a space elevator, the team will start with a general goal for systems engineering of a space elevator; a list of pragmatic principles; a set of initial

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[73] *Systems Engineering Handbook*, INCOSE, Version 2.0, July 2000, p. 13.

concerns; motivation and vision; and, identification of systems trades for the Wright-Flyer version.

Table 4.4, Mega-Projects[74]

Category	Mega-Project	Price ($ Billions)	Comments
Space	Space Elevator	6.2	Estimate for Wright-Flyer
	International Space Station	60 +	Estimate for 2005-16
	Crew Exploration Vehicle	6.6	Preliminary estimate
	Prometheus	1.5	Nuclear electric propulsion
	Space Debris Monitor	7.0	Estimate for new, more precise system
	IRIDIUM Constellation	5.4	92 satellites launched
Aeronautical	7E7	11	Incremental from 707, 747
	Comanche	11.0	Spent funds + termination
	US Missile Defense	> 60	Estimate for shield
Buildings	Taipei 101 Tower	0.7	508 meters high
	Environmental Mission	1-2	910 meters for energy
	Mega-City (Japan)	800	2004 m, one million people
Bridges	Akeshi	4	4 km length (1.9 km)
	Sicily to Italian mainland	5	3.2 km single span
	Oresund Bridge	3	Denmark to Sweden
	Big Dig (Boston)	14.6	Grew from estimate of 2.6 B
	Channel Tunnel	13	Loosing money
Other	Yucca Mountain	60	100 km of access

4.4.2 Goal The systems engineering goal should be to "Enhance the space elevator development though engineering insight." In this category is the critical step of "selling" the space elevator to

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[74] Raitt, David, and Bradley Edwards, "The Space Elevators: Economics and Applications," International Astronautical Federation Congress, Vancouver, Oct. 2004.

stakeholders and investors using engineering knowledge and credibility.

4.4.3 Pragmatic Principles During the development of a complex system, a set of pragmatic principles proven throughout past mega-projects will help tremendously. A set of these principles and some potential impacts are:

- *Know the problem, customer, and consumer.*
  The global mobile satellite industry lost over $12 B due consumer reluctance.
- *Use effectiveness criteria based upon needs to make system decisions.*
  The Chunnel "high speed" needs push many requirement support decisions.
- *Establish and manage requirements.*
  International Space Station requirements are still in flux after 15 years.
- *Identify and assess alternatives so as to converge on a solution.*
  Access to orbit is still using rockets based on 1940's concepts.
- *Verify and validate requirements and solution performance.*
  Electric cars are now running into trouble with fire departments for caustic chemicals.
- *Maintain the integrity of the system.*
  The internet open standards are based on massive efforts to maintain effectiveness.
- *Use an articulated and documented process.*
  Systems engineering discipline is being folded into the software efforts of the Carnegie Mellon Software Engineering Institute.
- *Manage against a plan.*
  The maturity of the plan stays ahead of the rest of the development program to ensure efficient program management.

4.4.4 Initial Concerns Early in the process, the systems engineering team for the space elevator must identify initial concerns.

This is critical so that the team can focus on major stumbling blocks and assist in mitigating or avoiding them. Some of the customers and their concerns are shown below.

Table 4.5, Customer Concerns

Customer	***Concerns***
Stakeholders	Vision leadership in place? How much investment? Who else is invited to participate? How much control do I receive?
Paying customers	How long is the trip on the Elevator? What is the reliability of elevators? What is the size/shape/mass of payloads to altitude? When is the first logistics trip planned?
Construction crews	Platforms at what altitudes? Can construction be accomplished from Earth? Where are the habitat nodes for on ribbon workers? Where do the crews spend work/leisure time?
Investors	How many space elevators? When? How much is the first investment? What is the payment schedule? What is the return on investment and when?
Operators	How comprehensive are the ground operations? Who will write Mission Operations Concept? When? How many operators on duty for each shift? What type of operations facilities are required? What type of backup operations facilities are required? How many climbers? Per day? On the elevator at once?
Environmentalists	What is the reliability and safety of a space elevator? What is the impact of the construction? What is the impact of the traffic to and from the base station? What is the impact on the Earth's orbital environment? What are the benefits vs. rocket exhaust impacts?

4.4.5 Requirements Foundation New mega-projects need to define requirements to ensure that builders know what to construct. A requirement describes what must be "accomplished, transformed, produced, provided or constrained."[75] The requirement lays out what must be done while the systems engineers and systems managers determine how to fulfill the requirement. Requirements management is key to excellent systems management. It must be started as early as possible, accurately tracked, and rigorously verified. The first step is to identify the requirements and lay them out in a Systems Requirements Review document. This should outline for the whole team what must be accomplished during the development of the system. The next step is to analyze the integrated requirements to ensure that they do not conflict and that they interrelate and cover the areas of concern between systems and subsystem, as well as top levels. The third step is to identify and resolve issues as soon as they surface within the realm of systems requirements. A consistent and understandable set of requirements early in the program will lead to a better understanding of what must be accomplished and enable success. Throughout the systems development cycle, the requirements must be evolved as a part of the system life cycle. It is a proven point in systems development, especially in space systems of extreme complexity, that early identification of systems requirements is mandatory and will assist the team in its successful completion. Lack of a complete set of requirements can lead to major schedule slips and massive cost increases. Requirements are derived from many sources as shown in Figure 4.4.

> "The primary objective is to establish a database of baseline system requirements derived from the source, to serve as a foundation for later refinement and/or revision by subsequent functions in the systems engineering process and for a non-ambiguous and traceable flow down of source requirements to the system segments. This database foundation needs to be as complete and accurate as possible and must be fully traceable to source documentation. As a minimum, this foundation must include:
>
> - Program requirements
> - Mission requirements
> - Customer specified constraints

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[75] INCOSE organizational pamphlet 1997.

- Interface, environmental, and non-functional requirements
- Unclear issue discovered in the requirements analysis process
- An audit trail of the resolution of the issues raised
- Verification methods required by the customer."[76]

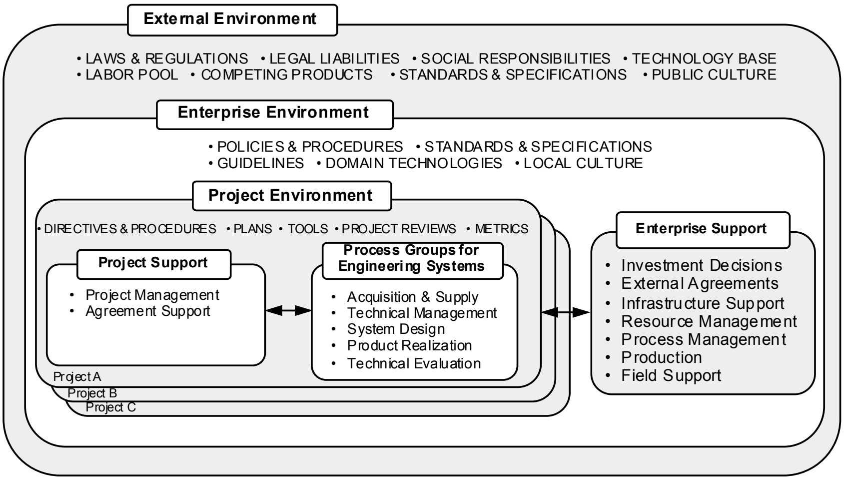

Figure 4.4, Requirements Sources[77]

The systems engineer and program manager want to have a set of allocated requirements located in the Systems Specification Document and matched to the Requirements Traceability Matrix. The approach is to:

- Allocate all requirements to components, subsystems, and systems
- Ensure functional performance requirements are allocated to all components of architecture
- Throughout the life cycle, ensure the traceability from source documents is maintained

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[76] INCOSE Systems Engineering Handbook, web available, 2000.

[77] INCOSE Systems Engineering Handbook, web available. 2000.

- Keep a history of all requirements and their adaptations from the originals

Traceability from the original customer specification is important as the design progresses and matures. Many documents and software packages have been developed to help in this process. To ensure traceability through to operations and the end of the life cycle of a system, the team must ensure that the verification and validation criteria are established early; test planning reflects the status of the requirements fulfilled; final satisfaction of specific requirements is recorded and the responsible engineer is continuously available for review from within or without the project team.

As each requirement is developed and recorded for the team, many questions must be asked to ensure that the requirement is real and meaningful.

- Is each requirement clear?
- Is each requirement a proper requirement?
- Is the requirement necessary?
- Is each requirement consistent with product standards?
- Is each requirement achievable?
- Do the requirements pass the traceability test?
- Is each requirement verifiable?[78]

Throughout systems development, requirements will be reviewed, assessed and quantified. However, the critical step in the development of requirements is the Systems Requirements Review where mission requirements and system requirements are analyzed, allocated, and validated. This usually occurs prior to significant systems reviews such as the Preliminary Design Review or the Critical Design Review.

4.4.6 Systems Engineering V To fully understand the growth of a program, engineers and managers must realize that the process is in the shape of a "v". At the beginning, the analysis is at the system's top-level. At the end, the system has been put together and tested at

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[78] INCOSE Systems Engineering Handbook, web available. 2000.

the systems level to verify requirements and validate the needs of the customer. Through successive iterations systems engineers are responsible for ensuring that the system is decomposed into definable parts, designed at component levels, tested and verified at lower levels and larger scales, and then assembled. This process enables the systems engineer to attack intractable problems by breaking them down to more manageable issues and then testing and validating the solutions. This is shown in Figure 4.5.[79]

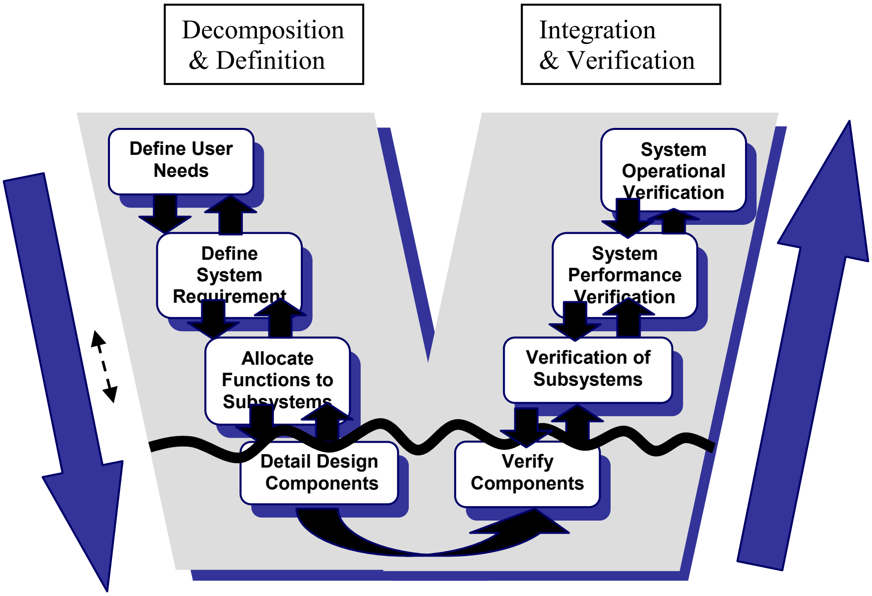

Figure 4.5, Systems Engineering V[80]

4.5 Space Elevator Motivation

An initial step in all mega-projects is to justify the expenditure of resources. This is usually accomplished in parallel with an initial systems concept development leading to an approval to spend significant funds on the project. Included in this step is the development of a vision for the mega-project and a concise list of reasons to proceed that justifies the project. The systems engineer,

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[79] "SMC Systems Engineering Revitalization," an AX Briefing, Col. Horejsi 2004

[80] "SMC Systems Engineering Revitalization," an AX Briefing, Col. Horejsi 2004

systems architect, and program manager work together to create the motivation to proceed.

4.5.1 Vision Development No one can hope to complete a mega-project alone. These projects take years of effort by thousands of dedicated experts in many fields. In the case of a space elevator it will take physicists, material scientists, accountants, politicians, salespersons, artists, engineers and numerous other types of very talented professionals. The common thread that can bring a team like this together and drive them in a single direction is a vision, a grand vision worthy of a committed career. Ask the men and women of the Apollo program who were each inspired by the vision. The same type of grand vision that drove the Apollo program can drive a space elevator effort. The vision must be clearly articulated and become a contagious dream to drive thousands to dedicate their lives and millions to support it. In the 1960s, the dominant vision was to place a man on the moon. What is the motivation to drive humanity at the opening of the 21st century? We all require food, air, shelter, etc. These are the necessities of life but rarely constitute a driving vision. Visions are based upon dreams of a better life and escape from what keeps us tied down. Grand visions are based upon achieving greatness, immortality, recognition. How about saving the world, or opening a new world for our children? These are visions that could be attached to a space elevator.

We have all heard of the problems in our world. Issues such as AIDS, war in the Middle East, terrorism, globalism, and weakening economies are more immediate but pale in comparison to the larger, unstoppable threats that will face us and our children in the coming decades.

> ***Population:*** The Earth may not be able to support the increasing number of humans.
>
> ***Energy:*** We are running out of the fossil fuels that are the cornerstone of modern society.
>
> ***Pollution:*** Our various activities are affecting the Earth and may soon create massive global warming or an ice age.

> ***Global Catastrophe:*** An asteroid hitting the Earth could be a small disaster, a city killer or a global transformation.

In a recent *National Geographic Magazine*, an article on China clearly illustrated the current state of energy and pollution problems that will grow into an unbearable dilemma in the coming decades. With a population of 292 million, the United States uses the equivalent of 2.3 billion metric tons of oil and produces 5.8 billion metric tons of carbon dioxide a year. With a population nearing 1.3 billion, China uses less than a half of this energy and produces a little over half the carbon dioxide. With the Chinese rapidly converting to an industrial society, the impact on global energy consumption and pollution will be dramatic. India and Pakistan are not far behind in their population growth. To truly understand the global impact we must also remember that we may be near the peak of global oil production. What will the world be like for our children? How do we change the future that is developing? There are six billion human beings and we have clearly demonstrated their capacity to affect the world and its future.

4.5.2 Creating and Maintaining a Vision Having the basic vision is a beginning. However, the vision is valuable only if it can be made real, if it is clearly articulated and if a detailed plan for moving from the current state to the goal exists. The space elevator concept has existed in various forms for decades, even centuries, but only with recent efforts has it become a project that can be realized. A viable engineering plan (with no requirement for new physics) and an affordable program have been developed. The mega-project has begun to capture the interest of critical federal agencies and the imagination of the public. The project is taking root but it has been slow to become formalized. After originally stumbling on the concept and being intrigued, but not inspired, it took some time before the grand vision became a seed for initial work. The prior work was too large, too far beyond what existed and had too little to justify its claims. As in such cases the audience is entertained but not inspired to participate, the returns are too uncertain, the direction to proceed too nebulous. As stated above it was not a vision to inspire masses but enough to inspire one. In the case of a space elevator the initial vision was enough for it spread to a small handful of people in the first year. This was sufficient to keep the project alive and the vision refined. Within a year the basic engineering concept was laid out and began to grow and spread. It was still vulnerable but was strong enough to begin enticing a group of loosely connected supporters. By the end of the first year enough of the engineering details of the concept had been examined to answer most of the basic questions and concerns. The grand idea has grown to an operating program with goals, schedule, detailed plans and understanding of the true implications of success. People can see where they can get involved; where they can play a part; why it is important; and, that the return will be in a specified amount of time. However, with growth, the project now faces a new set of dangers. More participants mean more opinions and with a multitude of inputs the expectations can get derailed. The mega-project can get modified in directions lacking inspiration. Key aspects of a driving vision are that it must be inspiring and attainable. It must seem almost beyond imagination but also be realistic in all aspects. Lose either aspect and the project will die. Let's look at some of the strains that have threatened a space elevator.

Modifications to Concept: Modifications that offer increased performance are tempting but must be considered carefully in terms of what they will cost the overall system. Does the added performance come along with increased risk or complexity? Would this added risk or complexity tip the scales on whether the entire system can be built? An operating basic Wright-Flyer space elevator with no bells or whistles, long travel times, and inefficient subcomponents is a dramatic improvement over current rockets. In itself it is a driving vision, no better system is required. If a modification is made that improves the system but makes it more difficult to sell from a risk and complexity standpoint then it is probably not an overall improvement. Modifications include looped ribbons, orbital tethers with space planes, oscillating ribbons, multiple legs, beamed or conducted power, unmanned or manned cargo, alternative materials, and many more. The key to maintaining a project is to inspire and make the goal attainable. The primary threat to the success of the space elevator is the believability of the concept. An elevator is a monumental step forward and the first question is whether it is possible. With this understanding, maintaining the project has taken on a clear mantra – keep it simple. Maintaining the vision means taking the simplest route, the simplest solution and reduce complexity and risk, at all costs.

Changes to Direction: Changes have also been suggested: work with the military; don't work with the military; build the first one on the moon or an asteroid; work with the big aerospace contractors; avoid the big aerospace contractors; work with NASA; don't work with NASA; make it international; and, keep it American. The amount of advice is constantly increasing. Unlike the threat of a fatal modification, the impact of a change in direction is harder to quantify although it can be just as lethal to a project. With the new NASA initiative to go beyond Low Earth Orbit, a test space elevator on the moon has been considered. This would match with the NASA initiative but have less value as inspiration. A close alignment with NASA may be required to move the program forward if the political winds blow favorably. Similarly, selecting to pursue an international effort could have positive or negative impacts. The more support the better in general; but, diverse major support with political ties can adversely affect the direction of a program. Large international programs are sluggish at the beginning and can collapse and stall under their own weight. If the direction is set incorrectly, the system could go down a dead end and loose the strength of its vision.

Fine Line to Walk: The above mentioned temptations must be carefully examined to ensure the project and vision remains intact. We can not lose inspiring attributes. Setting expectations for the global team of stakeholders and investors must be stabilized in order to maintain continuity. It is a fine line to walk. The vision and how the project is implemented is key to either success or failure.

4.5.3 Apollo Comparison The Apollo program is an example of a mega-project that succeeded. The technology was not revolutionary: rockets existed, just not engineered to go to the moon; capsules for supporting humans existed, but not for space. The goal was simple and set to place a man on the moon and return him to Earth within eight years. The added push was the competition between the United States and the Soviet Union. The Apollo vision had the critical components: an inspiring vision and a believable program. It was a grand vision that drove a nation. The true artistry by which the vision was conceived and maintained is clear when the details of the program are examined. The goal of the Apollo program was to place a man on the moon and return him safely to Earth. The Apollo program did this and precisely this. There was really little else to the program. There was little tangential technology, no follow-on program, and no ancillary missions. The vision was focused and remained focused. This is what enabled Apollo to achieve its goal. There were plenty of other options that could improve the program but may have derailed the vision: build a space station first, plan the first landing as part of a permanent base, make the launch system reusable, have the lander produce its fuel or oxygen from lunar resources, work with the Japanese or Europeans, etc. A modification to the program such as building a space station first could have killed the effort. Imagine making the argument that a station would reduce the long-term costs and help develop and test technology needed to go to the moon. Reasonable arguments, but the delay of a few years, the added immediate cost and the distraction could have diluted the vision and unfocused the goal. The drive could have been weakened, less inspiring and more difficult to see a clear path. Would it have killed the program? Hard to say; but, it is a possibility.

4.5.4 A Simple Vision Understanding the Apollo program and how its vision was instilled and used is critical to our current endeavor of a space elevator. We are not far from where Apollo started in terms of the available technology. We have an inspiring goal. A new space race between the United States and China is brewing though not at the level it was with the Soviet Union. One additional driver the current endeavor has, that was not part of the Apollo program, is the potential large economic return. Of course, another difference is the state of the world. The vision needs to fit the current culture. A simple vision that can change the world is:

Space Elevator Vision

The space elevator gives us the road to limitless opportunities while opening up the solar system.

4.5.5 Motivation Global problems require large-scale solutions. In this case one possible route to alleviate some of our major Earth-based issues is a space elevator. There are three remarkable motivational drivers for a space elevator; low-cost access to space, special location capability, and changing spacecraft design for new roles and environments. Each of these three will significantly impact the world we live in as well as space projects.

4.5.5.1 Low Cost Access to Space This motivation will drive to reality when it is shown that the true cost of the access to space would be lowered by a factor of 250 ($25,000/kg to orbit vs. $100/kg). Not only could current space programs benefit, but the low cost aspects would enable whole new businesses and capabilities to flourish in space. Two principle projects that would greatly benefit are Solar Power Satellites and inexpensive geosynchronous communications satellites. In addition, NASA exploration vehicles will be radically different if they can get to orbit for a fraction of the cost and no "shake-rattle-and-roll" on lift-off. The geosynchronous solar power industry has never materialized principally because it would take enormous funding to initiate the program with current launch fees. At the present time, the economics of such a program would not be profitable or self-sustaining. The capability to place communications satellites at the geosynchronous altitude for pennies on the dollar in launch costs would "enable" projects now restricted by investment dollars. The profitability of today could grow tremendously if the launch costs were divided by a factor of 250. In addition, the communications satellites would be designed differently – huge antenna, great power capabilities, extra computers and unlimited memory. The NASA exploration venture to Mars estimates 500 tons of spacecraft to be placed in Low Earth Orbit prior to the first trip to Mars. That would total approximately $100 billion in launch fees prior to starting for Mars. With the space elevator, the cost would become $50 million. This is a sizable differentiator! – An Enabler!

4.5.5.2 Special Location Capability The unique ability to place a spacecraft at any location along the 100,000 km long space elevator provides a capability not even thought of before. Two items that illustrate this are the Space Exploration Initiative (expanded upon in Chapter VII) and the Earth Protection role. This second item has recently been recognized as a need for humanity as the Earth could sustain an asteroid collision that could be a catastrophe.

A Mars transfer orbit injection without chemical propulsion from Low Earth Orbit could change the whole Moon/Mars architecture. This capability is due to a relationship between altitude above the surface of the Earth and linear velocity on the space elevator. As the altitude is raised, the linear velocity is increased. At the surface of the Earth, the rotation rate yields approximately 0.4 km/sec of linear velocity while at geosynchronous altitude, the velocity matches the orbital speed required to be in circular orbit (3.07 km/sec). As the radius/velocity increases, a location above GEO altitude results in a velocity on the space elevator sufficient (if released from the elevator) to sling-shot to the Moon. A little higher is a location for "free flight" to Mars without chemical propulsion (approximately 56,898 km altitude with an inherent delta velocity of above 4.121 km/sec). Can you imagine building a large spacecraft that does not need chemical propellant to escape the gravity well of the Earth which goes all the way to Mars?

Another capability on the upper reaches of the space elevator could enable spacecraft to maintain readiness for a mission while having an inherent velocity. This capability is a projected requirement for the protection of the Earth from asteroids. Currently, after the community has determined that an asteroid is going to collide with the Earth, the spacecraft has to be built, launched and then propelled out of Earth's gravity well. The Planetary Defense Architecture could be enhanced by locating defensive vehicles at the outer reaches of a space elevator for more timely release and less cost to orbit. Great amounts of time could be saved if the rendezvous spacecraft could be stored at an appropriate location along the space elevator for almost instantaneous release toward a threatening asteroid (at an altitude of 100,000 km, the inherent delta velocity is about 8 km/sec). This ability to park an Earth Defender on the space elevator would significantly cut response time, thus enabling Global Protection. The responsible team could, indeed, toss Global Protection spacecraft within one day after determining their preferred rendezvous location (one rotation of the Earth to align properly).

4.5.5.3 Open up Spacecraft Design Not many people have analyzed the changes in spacecraft design when a space elevator is successful. Two factors cry out for significant re-evaluation of spacecraft design when launched from a space elevator. The first is the absence of the "shake, rattle, and roll" of the launch phase. The stresses of an elevator will be far less than the launch of a pre-assembled spacecraft on a rocket or the shuttle. How would the design change if you could deliver parts to assembly locations and then operate in free fall for the rest of its operational life. Think of Fed Ex and Dell computers to visualize the change. The second design impact is the negation of chemical propulsion for escaping Earth orbit. The previous section talked about going to the Moon, Mars and Earth threatening asteroids rendezvous trips without chemical propulsion to escape the Earth's gravity well. This would have tremendous impacts upon design of spacecraft and on mission capabilities.

4.6 Wright-Flyer Trade Study Spectrum

The space elevator has a tremendous set of challenges that will keep systems engineers completely involved and constantly busy for years. The complexity of the individual items will be challenging enough without all of the issues of interconnectivity and compatibility between systems and subsystems. The next set of tables illustrates some of the major issues that a space elevator team must address early and propose initial solutions to move the whole project forward. Many times in a mega-project, the intimidation factor at the beginning is significant and requires systems engineers who can adjust to the unknown and adapt as complexity changes the direction of project development. Figure 4.4 illustrates the relationship between major space elevator segments and their sub-segments, and the components. In addition, it shows how interrelated the engineering relationships become as decisions are made in any one segment, subsystem, or component. Table 4.6 shows an example of the space elevator components inside the system-of-systems.

Table 4.6, Space Elevator Hierarchy Examples

Level	Definition	Example
System-of-Systems	A series of systems that are integrated to work harmoniously across the environment.	Wright-Flyer space elevator
System	An integrated set of elements, segments and/or subsystems to accomplish a defined objective.	Climber, power system, communications infrastructure, ribbon, countermass
Element or Segment	A major product, service, or facility of the system, e.g., the aircraft element of an air transportation system (commonly used, but subsystems can be used instead of element/segments).	Climber motor, laser power generator, GPS location devices

Subsystem [subcomponent level 1]	An integrated set of assemblies which performs a cleanly and clearly separated function, such as communications, electronics, structures, or controls; involving similar technical skills, or possibly a separate supplier.	Climber motor wheels, laser power diodes
Assembly [subcomponent level 2]	An integrated set of components and/or subassemblies that comprise a defined part of a subsystem, e.g., the fuel injection assembly of the propulsion subsystem.	Climber motor wheel assembly package
Subassembly	An integrated set of components and/or parts that comprise a well-defined portion of an assembly.	Wheels, laser lens, GPS chips
Component	Comprised of multiple parts; a cleanly identified item.	Structure for wheels, box for electronics
Part	The lowest level of separately identifiable items.	Individual items such as bolts, nuts, glue, insulation material

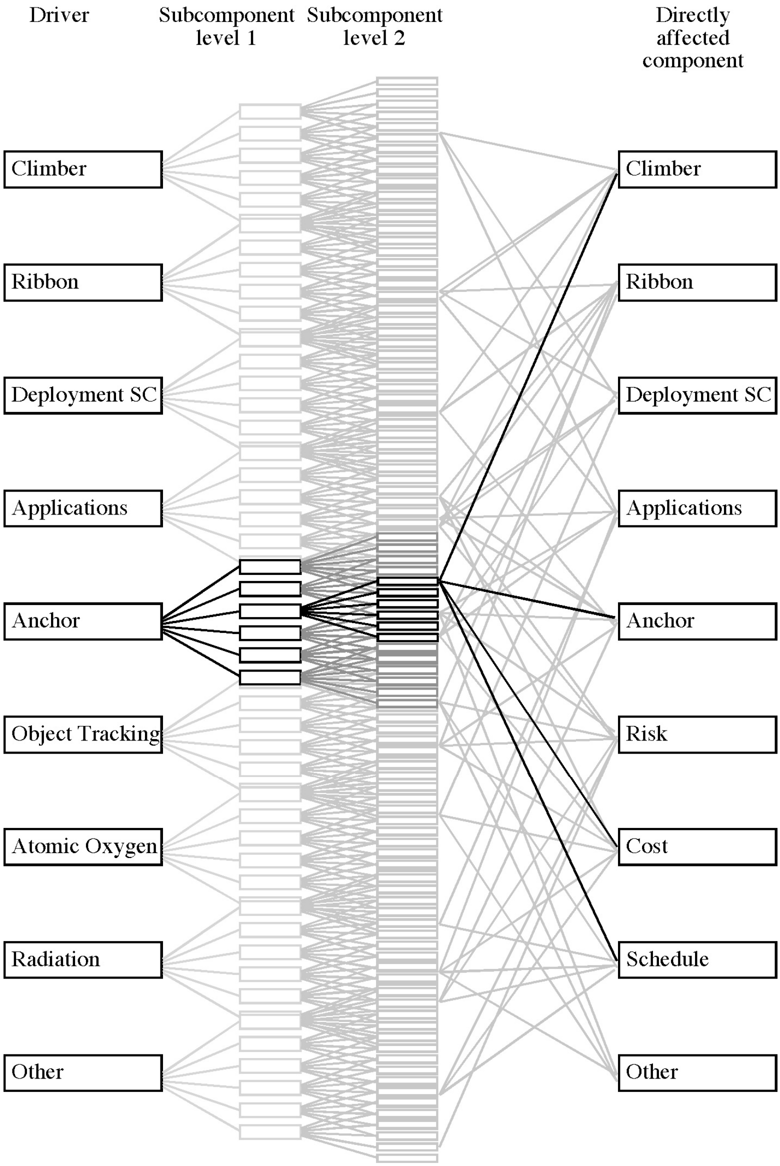

Figure 4.6, Complexity Diagram[81] (note: SC is spacecraft)

Early recognition of the complexity of a mega-project can indeed facilitate reduction of risks through early technology development efforts. At this point in the development of a space elevator more questions have surfaced than answers - a natural phenomena early in

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[81] Edwards, Bradley, "Status of the Space Elevator," International Astronautical Federation, Oct. 2004.

a mega-project's lifecycle. The following tables illustrate the current complexity of the challenge of fielding a space elevator.

Table 4.7, Guide to Trade-off Matrices

Trade-off Complexity Matrix	Table Number
Spacecraft size, propulsion, power, launch, assembly, and deployment	4.8
Ribbon material, design, coatings, size and alternatives	4.9
Climber velocity, drive motors, and power	4.10
Politics such as an international project or involvement with the military	4.11
Environmental issues for a space elevator	4.12
Tracking issues such as sensors and communications	4.13
Anchor items such as power	4.14
Power issues such as laser, beamed radio frequency, conducted RF and locations	4.15

Table 4.8, Spacecraft Complexity Trades

Detail level 1	**Detail level 2**	**Impacted component**	**Implications**
initial ribbon	size	risk	Risk of damage and destruction to the ribbon exponential decreases as ribbon thickness and/or width? Increases?
		schedule	The wider, thicker or longer? the ribbon the shorter the schedule of? - linear dependence?
		climber	The wider, thicker, or longer the ribbon the larger the initial climber - linear dependence.
		spacecraft	A wider, thicker, or longer ribbon requires a larger support system and size is limited by the capabilities of the launch vehicles available - structure is linear dependence-fuel exponential increase with ribbon size.
deployment	spooling	ribbon design	Spooling determines the ribbon design, width, flexibility required, and the risk of twisting and tangling.
		spacecraft	Combining spools - End or side uncoiling
	altitude	schedule	Optimal altitude reduces the deployment schedule
propulsion	electric	power system	The electric propulsion requires high power. This power can be supplied by the power beaming but it will impact the design of the power beaming system. Tracking, scheduling and location of the power beaming system will be the main considerations.
		schedule	The electric propulsion will require a much longer time (6 months to years) to move the spacecraft from LEO to GEO. A solid rocket engine would move in days.

		risk	Development risk - Longer spacecraft operation - longer time in radiation belt
		ribbon	Due to the higher efficiency and lower fuel mass a larger initial ribbon can be deployed
		spacecraft	Reduced structure requirements
	chemical	ribbon	A smaller initial ribbon can be deployed with the same launchers than for electric propulsion.
		schedule	Faster move from LEO to GEO
		risk	Low development risk - shorter spacecraft operating time - less time in radiation belts
		spacecraft	Heavier structures for fuel - exponential growth
power system	nuclear	regulatory	Extensive regulatory requirements
		launch	Limits on launch – political, environmental?
		cost	expensive direct and indirect costs
		spacecraft	Can be used for electric propulsion
	beamed	power sys	Simple, mature technology
			Lightweight system
		schedule	Less than 100% duty cycle will increase schedule
		risk	Well understood transmission concept
		spacecraft	Must operate in low-Earth orbit with <100% duty cycle
			Must orient to the laser power beaming
on-orbit assembly		cost	Manned on-orbit assembly is likely to be much more expensive in current environment
		schedule	Manned assembly has much higher schedule uncertainty
		spacecraft	Autonomous assembly is more complex
			Manned assembly more expensive but less risk

Table 4.9, Ribbon Complexity Trades

Detail level 1	**Detail level 2**	**Impacted component**	**Implications**
material	strength	cost	Higher strength will be more costly to develop and to produce
		Ribbon design	Lower strength means larger taper and larger overall ribbon mass
		risk	Lower strength equates to increased risk due to lower safety factor
	surface	climber	A low friction surface on the ribbon means more challenges in the friction drive
Design variations	Large scale	risk	Design schedule directly impacts mega-project schedule
	LEO width	risk	Wider ribbon will reduce risk of severing the ribbon due to LEO objects
			Wider ribbon may increase possible climber damage
		climber	The width of the ribbon will affect the climber design
	Width within atmosphe.	risk	Reducing ribbon cross sectional area perpendicular to wind forces will reduce the risk of damage due to aerodynamic drag heating
		climber	Thinner width will be more challenging for climber traverse
	thick vs. wide	risk	Probability of impact from orbital debris and micrometeorites is dependant on both parameters
		climber	It is more difficult for climber to adjust to variable width than thickness
	length	operations	The quantity of destinations increases as length increases. Ex. at 100,000 km the ribbon can throw to Venus and Asteroids, at 119,000 km Jupiter is reachable

coatings		risk	Damage to the coatings will allow Atomic oxygen to enter and erode fibers
		climber	Climbers must produce minimal wear on the ribbon and not damage the coatings - minimal pressure and slippage
		operations	Re-coating of the fibers may be required due to wear
Initial size		risk	The larger the cross sectional area of the initial ribbon the faster the build-up and lower the risk of fatal damage at early stages
		cost	The larger the size of the initial ribbon, the larger the payload mass, thus an increase in the required spacecraft launches - linear dependence
		climber	Increased cross sectional area of the initial ribbon could support larger initial climbers and payload masses
	deployment	risk	The larger the ribbon the more challenging the deployment
	schedule	operations	The larger the initial ribbon's cross sectional area the shorter the construction schedule of subsequent elevators - ~6 months for every factor of two in size
Alternative designs	tube	climber	Inside diameter restricts the width of the climber
		risk	Increased risk by a factor of at least 2x due to the symmetry of the structure (i.e., incidental impact and existing impact)

Table 4.10, Climber Complexity Trades

Detail level 1	Detail level 2	Impacted component	Implications
velocity trade	constant power	power system	Power beaming and power receiver on climber are simple- velocities range from > 20 mph to 120 mph
		climber	Drive system runs at variable speed through Earth's gravity well
	constant speed	power beaming	Requires high power at Earth and less at increasing altitude ranges
		climber	Constant speed drive is easier and lighter to gear. Motor must handle higher currents.
			More complex power system
drive	friction: tread	ribbon	Flat ribbon design
			Designed to survive tread transit
			Tread must account for contraction of ribbon during transit - if climber is at the limit of mass then the contraction could be 1 - 10%
			Tread has low pressure on ribbon - pressure is linear with tread area
			Ribbon must center climber - passive centering is preferred
		climber	Simple, mature technology
		risk	Wear and tear on ribbon, reduced efficiency due to bending of tread
	friction: roller	ribbon	Flat ribbon design
			Bending over rollers wears ribbon
			Higher pressure on ribbon than tread design
			Ribbon/rollers must work together to center
		climber	Simple, mature technology
		risk	Wear and tear on ribbon and rollers, reduced efficiency
		schedule	Limited velocity implies slower delivery schedule to orbit

magnetic	ribbon/climber	Specialized round or coated ribbon
payload	operations	The heavier the payload the slower the ascent or larger motors on climber required
	climber	Larger payload requires larger climber
splicing	risk	Robotic splicing complex and untried
	ribbon	Sharing of stress evenly among fingers of splice
disposal	regulations	Storage of climbers in orbit could be the subject of regulations
	operations	Disposal or reuse of climbers will impact how the elevator is used
	cost	Cost trade-off of disposal vs. reuse is complex
	salvage	Use of the climbers for parts in future applications, may be a reasonable business model
	schedule	If climbers are to be reused then the elevator will need to be shut down when the climbers are brought back down

Table 4.10, Climber Complexity Trades (continued)

Detail level 1	**Detail level 2**	**Impacted component**	**Implications**
Anchor –Based power	laser beamed	Schedule	Reasonable power levels will enable 8 day travel from Earth to GEO
		operations	Need tracking beacon on climber
			Climber must adjust for laser attenuation from cloud cover
			Shadow of ribbon on photovoltaic (PV) array could cause issues
		power system	PV array needs to supply high voltage to motors
		thermal management	Thermal/mass trades depending on Si or GaAs array
		Ribbon	Inadvertent heating of ribbon
		Regulations	Issues with reflections off of climber

		Risk	Low development risk
	beam RF	power system	Large receiver
		Operations	Similar receiver and converter to solar array
		Cost	Inefficient system increases operations cost
		Climber	large rectenna receiver
		thermal Management	Thermal trade for dealing RF heating
	conducted RF	Ribbon	Must be large (10 meters or more)
		Operations	Powers lower altitude climber only
		Climber	RF receiver
	conducted electrical	Ribbon	Two conductors with insulator
		Cost	Efficiency of transmission drops with distance, at GEO efficiency can be small fractions of a percent
		Operations	Difficult to power multiple climbers differently
			Damaged climber may short conductors
		power system	Simple
		Climber	Simple, low mass receiver
			Drives are high resistance to use power efficiently
On-Board power	solar	Schedule	Low power delivery slows transit dramatically
		Risk	Mature technology
		power system	None on Earth, only climber receiver
		Cost	Increase climber but reduced power beaming costs
		Climber	Receiver design is solar arrays with orientation actuators
	nuclear	Cost	Increased cost
		Risk	Radiation exposure to personnel and/or environment
		Climber	Climber will be much heavier with shielding requirements

Table 4.11, Political Complexity Trades

Detail level 1	Detail level 2	Impacted component	Implications
International consortium own & operated	education and space development	operations	Fewer countries and entities to protest operations. Stronger alliance to address space treaties.
		schedule	Increase in schedule delays because all activities must be coordinated among several countries with their policies
		cost	Complex interactions and utilizing more diverse manufacturers increase cost.
			Reduce finanicial stresses of each entity because costs are shared among several agencies
		risk	Redundant protection entities to maximize protection
			Stronger alliance to support and protect the anchor.
	military	operations	Increased probability that countries excluded from the alliance will protest operations
		risk	Increase likelihood of attacks by militaries not included in the alliance
			Established military or law enforcement entities to maximize methods and level of protection

Single entity owned & operated	education and space development military	operations	High probability of becoming a monopoly
		risk	Increase risk of attack because it would be seen as an unique military weapon

Table 4.12, Environment Complexity Trades

Detail level 1	**Detail level 2**	**Impacted component**	**Implications**
satellite debris	probability Of collision	Ribbon	Modification of ribbon dimensions to optimize survivability
	Orbital debris field changing	Ribbon	Orbital debris picture could improve resulting in less damage to ribbon.
Type of Debris	Movement	Operations	Active avoidance, maintenance Movement of the base and ribbon may require an opposing movement to damp the induced oscillation.
	Manned (Shuttle, ISS)	Ribbon LEO	Coordinated avoidance effort to Maneuver Spacecraft or move space elevator base
	Satellite or Debris > 10cm	Ribbon LEO to MEO	Movement of space elevator base to avoid debris
	Debris < 10cm	Ribbon LEO	Protection of ribbon from continual erosive effects
atomic Ox	surface	Ribbon	Coat the ribbon or design the ribbon to survive
		operations	Repair and maintenance
radiation	lifetime	ribbon	Design to survive radiation, modifications may increase size of ribbon

oscillation	dynamics	ribbon	The taper length and mass determine the natural period of the ribbon, modification of the dimensions will help damp the oscillations. Variations in lineal density and aerodynamic diameter may help dampen oscillations.
		operations	Active damping of oscillations may be required.
lightning	multiple legs	anchor	Location requirements
		ribbon	Conductive or non-conductive
wind	shape	ribbon	Narrower and thick inside atmosphere
	wave height	anchor	Locate where minimal winds
jet streams	constant	anchor	Locate where minimal jet streams
	altitude vary	ribbon	Minimize cross-section at level of high altitude winds. Subsonic and supersonic winds encountered varying with altitude.
hurricane	winds	anchor	Locate out of hurricane zones
induced currents		ribbon	Conductive/non-conductive sections to reduce the overall charging and currents
Orbital debris		ribbon	Modification of ribbon dimensions to optimize survival
Thermal Cycle	24 Hour Cycle	Ribbon Climber	Direct Solar heating expands and contracts the ribbon and changes its length. Climber encounters varying temperatures as it ascends the ribbon.

Note: ISS = International Space Station

Table 4.13, Debris Tracking Complexity Trades

Detail level 1	Detail level 2	Impacted component	Implications
sensors	optical	cost	New system to be developed
		risk	Increased development risk
			Better tracking reduces operations risk
	radar	Cost Operations	Mature system in use. Establish safety zone around space elevator ribbon to assess debris close approaches.
		risk	Lower accuracy increases risk
	array	risk	Multiple locations with good angles to debris
		cost	Multiple locations increase operations
	sensitivity	risk	Precise radio frequencies require sensitive parts
		cost	More sophisticated sensors are costly
		ribbon	Low sensitivity means impacts on ribbon from small objects, the ribbon must be more resilient
analysis	computers	cost	Large fast computers will shorten calculation times and will improve predictive assessments.
Communications	operations	risk cost	Essential communications must have line of sight to ribbon carriers Use of domestic satellites can insure communication at all times. Will add considerable operating costs.

Table 4.14, Anchor Complexity Trades

Detail level 1	Detail level 2	Impacted component	Implications
power	size	cost	The larger the power system - higher the cost.
		operations	Larger power systems will require more personnel and more extensive maintenance operations.
		power system	The power beaming system size will be limited by the power available on the station.
		anchor: drive	Larger power systems will allow for larger drives
		anchor: platform	The larger power systems will require more volume on the platform, more fuel storage.
	fuel	operations	The choice of fuel will drive the operations in terms of delivery, safety, regulations
	maintain	operations	Maintenance requirements will determine station need to go to dry dock and thus downtime.
drive	mobility	operations	Drive capabilities and mobility enable the anchor to move ribbon out of the path of satellites and storms.
			Mobility also enables the anchor to travel to drydock for maintenance. Higher speed and mobility means less down time.
		ribbon	The greater mobility reduces the number of collisions with the ribbon and reduces the required robustness of the ribbon
		cost	The better the drive the higher the cost. The reliability and lifetime affects the cost. The fuel used in the drive will impact the operations cost.

		risk	Mobility of the anchor reduces the risk from debris and storms. Also can induce strains on ribbon.
	size	operations	The larger the drive the more quickly the anchor can respond to requests to move.
	accuracy	tracking	The accuracy of the drive enables use of higher accuracy tracking.
		risk	The accuracy of the drive reduces of the possibility of impact by debris.
		operations	The anchor station will need to be equipped with a GPS and other navigation tools
platform	size	power system	The size of the platform can limit the use of RF and free electron laser (FEL) power beaming systems due to their required footprint. For FEL a length of about 150 m is required. Solid-state lasers require less footprint.
	stability	power system	A stable platform reduces the need for an optics system that can track the climber over multiple degrees, continuous on a fast timescale. The lower stability platform will result in higher power system and maintenance costs.
	robustness	operations	Robustness implies longer time between maintenance in drydock. Less-expensive operations.
	design	schedule	A better design for the platform, including high-quality housing and recreation, will reduce the schedule impacts due to the workforce needs to have time away.
		risk	A better design for the platform will reduce the stress of the workers and improve their performance.

Table 4.14, Anchor Complexity Trades (continued)

Detail level 1	Detail level 2	Impacted component	Implications
attachment	movability	operations	Removal required for transfer between anchor stations for repair and general dry dock.
	robustness	cost	Less repair and down time with greater robustness.
	capability	operations	Tensioning of ribbon and reeling of ribbon is required for proper and safe operation.
		risk	Proper execution of above operations will reduce the overall risk.
		maintain	Being able to reel in the ribbon to deal with malfunctioning climbers allows easy day-to-day operations
location	E. Pacific Equatorial	risk	This location minimizes risk from the weather.
		operations	This remote location impacts operations by making the trip to and from the anchor long and more costly. Maintenance and repair of the anchor require long travel distances or repair at sea.
			The extremely mild weather at this location makes operations easy in terms of maintaining location, stability and weather damage.
		anchor	The anchor must be very reliable due to the remote location.
		cost	The cost of construction of the anchor for this location is less than for other locations because existing oil platforms are close. General operations will be more costly due to the remote location.

	Australia	politics	Australia is not a principle space fairing nation
			Associated with many friendly countries
			Near Indonesia for equatorial location
		operations	Possibly close to major cities
			Ribbon goes up at an angle
		risk	Higher storm probability - more wind and lightning
		cost	Funding can be split
	land	operations	Movement on land is more difficult
			Easy access for cargo and people
			Plenty of room for people to live and facilities
		risk	Lightning is more prevalent
			Easy access for terrorists
		anchor	No anchor station

Table 4.14, Anchor Complexity Trades (continued)

Detail level 1	**Detail level 2**	**Impacted component**	**Implications**
alternatives	multiple legs	anchor	Multiple stations need to be coordinated to maintain tension
			More anchor maintenance due to larger number of anchors
		ribbon	Redundant ribbons at bottom mean additional mass though each leg can only support the same climber
			Dynamics are different than single leg
			Dynamics of a loss of a single leg
			Attachment point needs to be able to add and replace legs
			Attachment point needs to hold the tension
			Added mass of attachment and

		legs come out of climber mass
	climber	Ascend one leg, cross attachment point and continue up
		Smaller climber for same primary ribbon
		Climbs at an angle
	operations	More available integration time for attaching climbers to leg ribbon (~time for 1 leg x number of legs)
		Coordinate climbers from different legs
		Deployment is different, attaching legs
	power system	Possibly more, smaller beaming stations - each associated with a leg
	risk	Redundant legs reduce risk of loss at low altitudes
		Risk of attachment failure
	cost	Additional anchors
		Anchor maintenance
		Attachment point
		Additional ribbon complexity
		Additional power beaming systems

Table 4.15, Power Complexity Trades

Detail level 1	Detail level 2	Impacted component	Implications
laser	FEL	size	Requires large platform
		operations	Line of sight, no clouds
		regulations	Restrictions on open high-powered lasers near people, airplanes, etc.
	Solid state	cost	$100 per watt capital cost
			Major replacement of pump diodes every five years
		power beaming	30% wall plug efficiency determines power required
			No need for large station to expand beam
		risk	Megawatt laser power can damage airplanes, animals and nearby humans
		schedule	One kilowatt laser module has been built, current program pushing to build 100 kW and believe one megawatt laser possible - may need to couple lasers and consider 10-20% duty cycle for coupling
		operations	500 microsecond pulse, 10-20% duty cycle
			Easy operation, maintenance
			Transportable in small container
			No expendables
		climber	Wavelengths of 810 to 990 nm, receivers can be GaAs or Silicone depending on laser design
			Si receivers would imply a possible thermal issue
			High quality beam allows for small receiver diameter
		deployment	Small laser modules implies easy delivery to stations
			Small laser modules imply easy dispersion to global locations for use during deployment and then relocation for standard operations
	primary optics	lens	Heat and pointing

Table 4.15, Power Complexity Trades (continued)

Detail level 1	Detail level 2	Impacted component	Implications
beam RF	antenna	climber	Large receiver
	cycle time	operations	Transmitter is not movable, line of sight, no clouds, near power plant
		cost	Inefficient power delivery, very large transmitter, additional power plants
	ITU	regulations	Restrictions on beamed power and safety
Conducted RF		ribbon	Metal coated
		climber	RF receiver
		operations	Difficult with multiple climbers
conducted electrical	weight	ribbon	Dual conductors with insulator between them
	coupling	climber	High resistance motors required
	ground	anchor	Power at anchor
		operations	Complexity added by multiple climbers
	loss of	risk	A conductor sever could cut power, lightning rod discharge into ionosphere.
locations	deploy	regulations	During deployment it will be useful for the power stations to be located at widely spaced locations on Earth. This will require international cooperation.
		anchor	The anchors may need to be mobile if they need to be at different locations during deployment and operations.
anchor	size	cost	The larger the power system - higher the cost.
		operations	Larger power systems will require more personnel and more extensive maintenance operations.

		power system	The power beaming system size will be limited by the power available on the station.
		anchor: drive	Larger power systems will allow for larger drives
		anchor: platform	The larger power systems will require more volume on the platform, more fuel storage.
	fuel	operations	The choice of fuel will drive the operations in terms of delivery, safety, regulations
	maintain	operations	Maintenance requirements will determine station need to go to dry dock and thus downtime.
climber	solar	schedule	Low power delivery slows transit dramatically
		risk	Mature technology
		power system	None on Earth, only climber receiver
		cost	Increase climber but reduced power beaming costs
		operations	Slowed
		climber	Receiver design could be solar arrays with orientation actuators
	nuclear	schedule	Risk, cost, personnel protection

Note: ITU = International Telecommunications Union

4.7 Systems Engineering Concern

The use of space systems engineering has enabled the space arena to achieve marvelous successes. Table 4.16 shows some failures over the last fifteen years. The reality is that each project is unique with a new technology being implemented. Technological surprises occur and must be allowed. There are lessons learned that must be reviewed periodically to ensure that mistakes are found and acknowledged prior to big decisions.

Table 4.16, Why Do Satellites Fail?[82]

Date	Program	Problem/Outcome	Eng Mistake	Tech Surprise
04/90	Hubble	Severe mirror aberration due to a defect in the instrument used both in manufacturing and in QA.	X	
07/92	TSS-1	Deployment mechanism jammed by a bolt added after Integration and Test	X	
09/92	Mars Observer	Lost contact after re-pressurization of the propulsion system, probably due to oxidizer leak.		X
08/93	NOAA 13	An overly long screw shorted the battery charger.	X	
10/93	LandsatF	Pyrovalve blow by ignited fuel.		X
01/94	Clemen-tine	CPU froze due to data handling overload, allowing the thruster to continuously fire, depleting the fuel.		X
05/94	MS11 2	Contact lost, probably due to micrometeoroid/debris impact, charging, or combinations thereof.		X
02/96	TSS-1R	Severe arcing due to contamination within the insulation layers burned the tether.	X	
08/97	Lewis	A technically flawed guidance & control design caused tumbling-not promptly arrested due to inadequate monitoring.	X	X
10/97	STEP-4	Damaged by launch vibration — ground test deemed inadequate.	X	

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[82] Dr. Cheng SCSRA Brief, The Aerospace Corporation, 15 May 2003.

10/98	STEX	Solar array ran too hot, causing solder joint fatigue and severe performance loss. Thermal analysis done on wrong configuration.	X	
12/98	MCO	Metric/English unit mix-up in flight software, coupled with vulnerable navigation scheme, caused probe loss.	X	
01/99	Mars Polar	Touchdown sensors not protected from deployment shock, Lander causing premature engine shutdown.	X	
03/99	WRE	A starting transient from the pyro electronics controller prematurely ejected the telescope cover.		X

A very interesting curve was developed out of the NASA Comptroller's office that identified as the "pay me now – or pay me later" chart. This identified cost overruns for space programs within NASA and the amount of systems engineering conducted, as a percentage of the total cost. This curve illustrates why systems engineering has been supported. Management realizes that without significant and early systems engineering, programs have trouble and cost more than estimated. Figure 4.17 shows this.

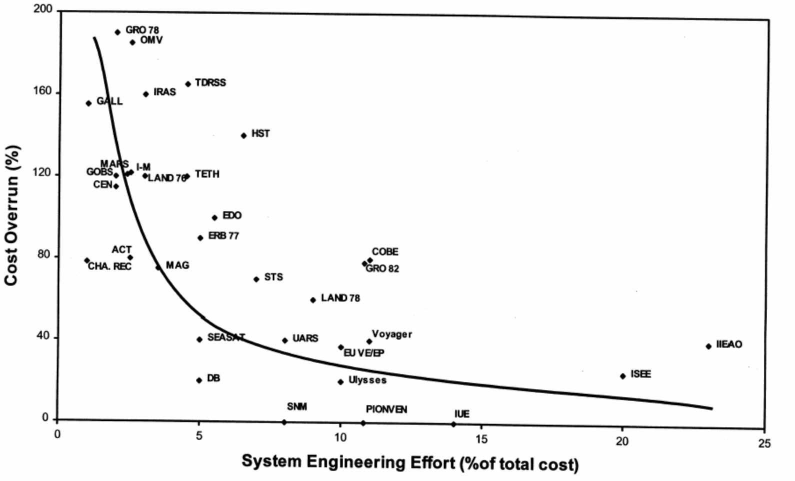

Figure 4.7, Pay me now – or pay me later[83]

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[83] Horejsi, Col. James. SMC Systems Engineering Revitalization Briefing, 2004.

4.8 Trade-off Studies

A space elevator will have many trade studies conducted during the conceptual development of the mega-project and many others during design, production, and operations over the lifetime of the system-of-systems. To expand upon the approach for these trade studies, and to examine three examples, the next three chapters look at significant issues that need to be addressed early, during the conceptual development of the system. They are:
Space Elevator, Survival, and Base Leg Infrastructure.

Each of the trade studies will be represented in an upcoming chapter using the Systems Engineering Process Task chart (Table 4.1), reflecting the importance of trade studies during the early phases of this project. The seven steps reflected will be followed in each chapter to establish a starting point for the future Wright-Flyer development program.

CHAPTER V – SYSTEMS ENGINEERING TRADE: SPACE ELEVATOR SURVIVAL

5.0 Introduction

Complex development mega-projects have challenges that excite and demand a commitment spanning half a career or more. The uniqueness of a space elevator is exciting for the designer and offers opportunities for imaginative and innovative thinkers. As shown in the previous chapter, there is a tremendous trade space open for the design of a space elevator. There are many questions and issues that must be addressed to enable a final design to be developed. As discussed in the chapter on systems engineering, the following tasks must be undertaken for a trade space analysis of this magnitude.

Table 5.1, Systems Engineering Process Tasks

	Systems Engineering Process Task	**Section**
1	Define the System Objectives (User's Needs)	**5.1**
2	Establish the Functionality (Functional Analysis)	**5.2**
3	Establish Performance Requirements (Requirements Analysis)	**5.3**
4	Evolve Design and Operations Concepts (Architecture Synthesis)	**5.4**
5	Select a Baseline (Cost/Benefit Trades)	**5.5**
6	Verify the Baseline Meets Requirements (User's Needs)	**5.6**
7	Iterate the Process through Lower Level Trades (Decomposition)	**5.7**

These tasks will be stepped through to illustrate a systems engineering process as applied to the space elevator survival. As such, the approach to a space elevator can be simplified by looking at basic ideas and approaching each issue as if it were the most critical item and not influenced by the complexity of the project. Simplicity in design is definitely a desirable outcome of early brainstorming for the development of a mega-project. The combining of simple concepts leads to more complexity; however, small pieces tend to go together instead of forcing a larger solution up from the bottom. Answers will surface and will be globally applicable. One approach this chapter incorporates is analyzing a space elevator along altitude lines. The characteristics of different altitude regions drive design requirements in different directions. This segregation seems to be natural and reflects the varying requirements of a space elevator design. The survival aspects of the design will be presented along the altitude segregation regions.

Table 5.2, Altitude Regions

Region	From (kilometers)	To (kilometers)
Super – GEO	36,188	100,000
GEO	35,386	36,186
MA	2,000	35,386
LEO	Aeronautical limit	2,000
Aero Lift	Sea Level	Aeronautical flight limit

[GEO – geosynchronous orbit @ 35,786 km; MA – Mid-Altitude; LEO – low Earth orbit]

The remainder of this chapter follows the systems engineering process tasks as guidance for a major trade study on space elevator survival. The resulting Requirements Fulfillment Matrix (Table 5.11) summarizes the systems engineering trade process accomplished in this chapter.

5.1 User Needs – System Objectives

The space elevator will be designed with many factors included in the trade space. Some anticipated desires of the customers and users for survivability of the architecture are:

- Zero Sever Infrastructure (the space elevator, once established as a Wright-Flyer moving cargo, can not fail)

  - Robust Ribbon (the ribbon must be able to take punishment and keep on operating)
  - Robust Situational Awareness (knowledge of the environment must be as complete as possible – better tracking of space objects and continuous surveillance of area around base leg infrastructure with inspection of all cargo)

5.2 Establish Functionality

This task leads to an analysis that is closely tied to operations. The user needs will drive the design from the beginning; however, the design will be expanded upon during later activities as more insight is developed about functionality.

5.3 Establish Performance Requirements

The basic requirements have been broken down into the customer needs and the resulting detailed requirements for the space elevator survival. The requirements are shown in Table 5.3.

Table 5.3, Performance Requirements

Basic	Detailed Requirements
Zero Sever	No catastrophic sever of space elevator ribbon
	Low occurrences of lightning
	No explosions on ribbon
	Low occurrences of high winds/hurricanes
	Laser power support does not melt ribbon
	No orbit/fly/float/drive within the space elevator corridor
	Debris/meteorites tracked and predicted
	Robust ability to move ribbon from major space debris
	Ability to move ribbon from major spacecraft
Robust Ribbon	Safety factor of 2.5
	Tolerance for atomic oxygen
	One-meter wide ribbon, curved for multiple hit avoidance
	Tolerance for bending modes
	Tolerant to climber forces
Robust Situational	Knowledge of solar/lunar effects (ultra violet, 7 hour oscillation, radiation)

Awareness	Tracking of satellite/rocket bodies
	Tracking of space debris
	Leadership in global debris mitigation efforts
	International policy creator/enforcer
	Enabler of debris reduction

5.4 Evolve Design and Operations Concepts

This task of the systems engineering process evaluates trade spaces around issues critical to success and formulates architectural solutions. The analysis for this section conducts trades leading to a space elevator survival infrastructure.

5.4.1 Altitude Breakout The rationale for segmenting the space elevator system into altitude regions is based upon simplicity and engineering scope. Solving local problems is always easier than solving global problems. This breakout enables the space systems architect and lead space systems engineer to compare and contrast engineering alternatives across the total project, allowing optimization at the appropriate level. Obviously, simple approaches inside a region might be expandable to other regions, or not applicable elsewhere. Hopefully, the insight gained by these analyses will yield an opportunity to lead design concepts and then systems alternatives. The chapter continues to look at the trade space with the following subsections:

Altitude Region
System Threat Breakout
    Survivability Remediation Techniques
    System Approach for Survival

But first, the following tables compare the altitude regions by basic characteristics and the effects upon design.

Table 5.4, Super GEO (Altitude > 36,186 km)

Characteristics	***Effects on Design***
Centrifugal force dominates	No power required to leave GEO
Low probability of collisions	Simplicity for backups
Launch location for solar system	Flexibility
Grow as counter-weight	Survivability and flexibility
Capture old GEO satellites	“Free mass” for counter-weights

Table 5.5, GEO (35,386 < Altitude < 36,186 km)

Characteristics	***Effects on Design***
Minimal survivability threat	Simplicity
Dominant during developmental phase	Center of mass and tension measurements
Critical transportation node	Work station (with or without people)
GEO node attach-detach as climbers pass altitude	Understanding of local dynamics and robotic grappling
Maybe GEO node not attached to space elevator – just floats along side	Creative design option needs to be traded

Table 5.6, Mid-Altitude (2,000 < Altitude < 35,386 km)

Characteristics	***Effects on Design***
Self deploy	Minimum design
LEO/MEO satellite nodes	Launch and inclination issues
Real debris issues (Molniya, GEO Transfer Orbit, Navigation orbits)	Survivability and redundancy
Electric propulsion probable	Simplicity
Radiation belts - lower region	Dump radiation
Tension monitoring – GPS location	Equipment and communications

Table 5.7, LEO (aero limits < Altitude < 2,000 km)

Characteristics	***Effects on Design***
Robust ribbons	Survivability and multiple tracks
Traffic control (up to 2,500 km)	Simplicity
Survivability of space elevator at greatest risk	Safety, security, move ribbon, curved surface, wide ribbon
Large radiation environment	Proper coating to materials Potential lowering of radiation inside electron and proton belts
Hotel for tourists at 100 km	Early revenue and work space
Laser energy efficient	Simplicity

Table 5.8, Aero Lift (sea level to aero lift limit)

Characteristics	***Effects on Design***
Minimum tension at connection	Simplicity and less stress
Multiple up and down paths	Redundancy and traffic management
Redundancy against terrestrial threats	Survivability
Base anchors distributed over large radius	Redundancy and flexibility
Traffic control in Command and Control Center	Local knowledge and flexibility
Lightning mitigation (laser illumination)	Survivability
Deploy prior to connection	Ease of space elevator deployment
Execute when ribbon deployed	Simplicity
Boat horizontal motion drive climbers vertical	Unique propulsion idea

5.4.2 Threat Breakout In order to propagate the vision of a space elevator a systems approach must be presented that addresses key threats to the survival over a projected lifetime. This chapter addresses the threats to a space elevator from meteorites, operational space objects, and space debris; proposes a series of realistic mitigation techniques; and, applies a systems trade approach resulting in a prioritization of techniques across the altitude domains. A systems approach to space elevator survival must address all threats from the expected environments. This ranges across many arenas, to include:

- Meteors and micrometeorites
- Space debris (expired spacecraft or fragments)
- Operational spacecraft
- Space environment (x-rays, gamma rays, atomic oxygen, cold/heat)
- Atmospheric environment (winds aloft, hurricanes, tornados, lightening, etc.)
- Human environment (aircraft, ships, terrorists, etc.)

The threats logically separate into five regions and encompass all basic issues that must be evaluated. Figure 5.1 is from the International Academy of Astronautics draft report entitled, Position Paper on Space Debris Mitigation Guidelines for Spacecraft[84].

Super GEO: This region has very little human-created debris, so the major threat consists of meteors and micro-meteorites.

GEO Region:This region has the micrometeorite issue and human hardware intersection. The advantage is that debris are mostly large and moving slowly when at, or close to, the "Geo Belt." The relative velocities are usually less than 10s of meters per second.

MA Region: This region is huge and mostly resembles the GEO region in that only a few man-made objects reside at this altitude. This includes a small number of objects right above the lower limit of 2,000 km altitude and around the 12 hour orbit populated by navigation constellations (GPS with more than 36 satellites; GLONAS with more than 20 satellites; and the future Galileo with more than 24 satellites). In addition, the Geosynchronous Transfer Orbit (12 hour, highly elliptical) leaves rocket bodies after payloads are "kicked" into GEO orbit. The velocity differences between a space elevator and orbiting objects for the 12-hour region debris presents a serious threat for a space elevator.

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[84] Hussey, John. Ed., Position Paper on Space Debris Mitigation Guidelines for Spacecraft, Draft ,– International Academy of Astronautics, 2003.

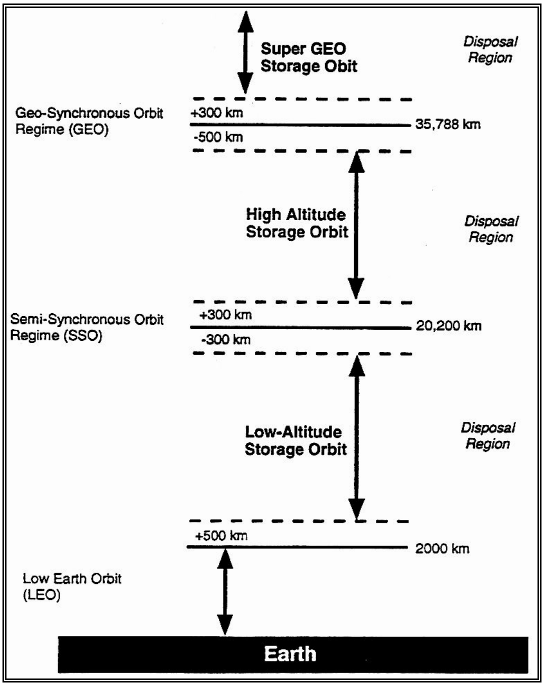

Figure 5.1, Altitude Regions[85]

LEO Region: This region has a major problem with space debris, a modest problem with operational satellites, and a smaller problem with micrometeorites. Most space debris have been created in this region filling all altitudes and inclinations, which results in equatorial crossing near a space elevator. Of the 11,000 objects tracked daily, approximately 8,000 are located in this region.

Aero Lift Region: The concern in this region deals with the dangerous aspects of the atmosphere that will threaten the ribbon and integrity of the space elevator. The dangers of concern are: winds aloft, hurricanes, tornados, lightening, and human interference (aircraft, ships, and terrorism).

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[85] Hussey, John, ed., Position Paper on Space Debris Mitigation Guidelines for Spacecraft, Draft – International Academy of Astronautics, 2003.

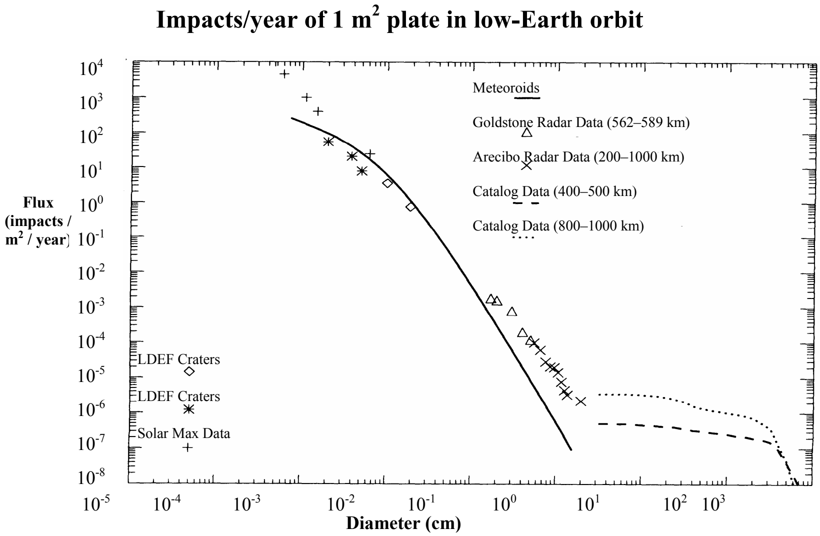

Figure 5.2, Impact Rates for Meteoroids and Orbital Debris[86]

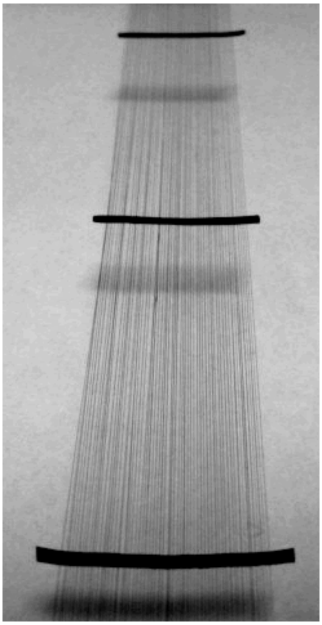

Figure 5.3, Ribbon Design[87]

5.4.3 Survivability Remediation Techniques The following techniques are designed as components in a systems approach to space elevator survival. Each technique can be used in each threat region; however, when assessing effectiveness or vulnerability reduction, some techniques are more reasonable than others in specific regions. In LEO alone, there are approximately 8,000 objects orbiting across the equator; and only approximately 5% are operational satellites that could maneuver for collision avoidance. If we use data from the debris community, an estimate can be made that a space elevator would be impacted by one of these objects (greater than 10 cm) every 1.2 years if not moved out

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[86] Larson, Wiley and James Wertz, *Space Mission Analysis and Design.* Ed. III._ McGraw Hill, 2002, p. 841.

[87] Pullum, Laura, Private Correspondence within Institute of Scientific Research, Aug 24, 2005.

of the way. This estimate is very preliminary and is directly related to the number of satellites, rockets, and fragmentation elements inserted into LEO. Dumping the LEO debris has significant benefits to a space elevator (see section on Debris Reduction).

Ribbon Design – In this case, the ribbon design refers to the analysis of various ribbon descriptions with respect to their ability to survive multiple hits over the ribbon's lifetime from the smallest meteorites and space debris. As the threat is from large numbers of small items of (less than 1.0 cm in diameter), the survival of a space elevator must allow multiple hits per segment of ribbon over its lifetime. The principle sources of these particles are meteorites and debris fragmentation, as shown in Figure 5.2. The current concept to mitigate this threat is to manufacture a ribbon that is tolerant to holes being punched through it. A picture of a current design is given in Figure 5.3. For larger items, the concept is to move the ribbon after warning of potential conjunction. This technique is to be used against the issues of survival of a severed main ribbon of the space elevator. The threat is from large debris, large spacecraft, and large meteors. All space elevator engineers and designers are concerned when they look at the current debris population of dead satellites, operational satellites, and old rocket bodies (as represented in Figure 5.4).

Debris Reduction – Policy – The belief that we can continue to operate with minimum debris reduction policies must be changed to responsible control of our space environment. The first steps were taken in 1998 with the approval of the Inter-Agency for Space Debris Coordinating Committee (IADC) and the International Academy of Astronautics (IAA) published[88] approach for debris mitigation. Major space faring nations are indeed incorporating space debris mitigation techniques in a modest way. It is good for the world community in the long run and must be mandated to be effective. There are many steps that have been implemented and the environment is safer because of the pioneering efforts, over the last 10 years, by a small group of space debris mitigation experts. This must be continued and re-enforced to ensure that no more rocket bodies fragment; no more GEO satellites are left in their operational orbits after mission lifetime; and, that no LEO satellites create smaller pieces during or after operational use. The current thinking inside the international

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[88] Technical Report on Space Debris of the Scientific and Technical Subcommittee, Report of the United Nations Committee On Peaceful Use Of Space. 1999.

debris community is that a policy could be implemented, and enforced, for "Zero Debris Creation."

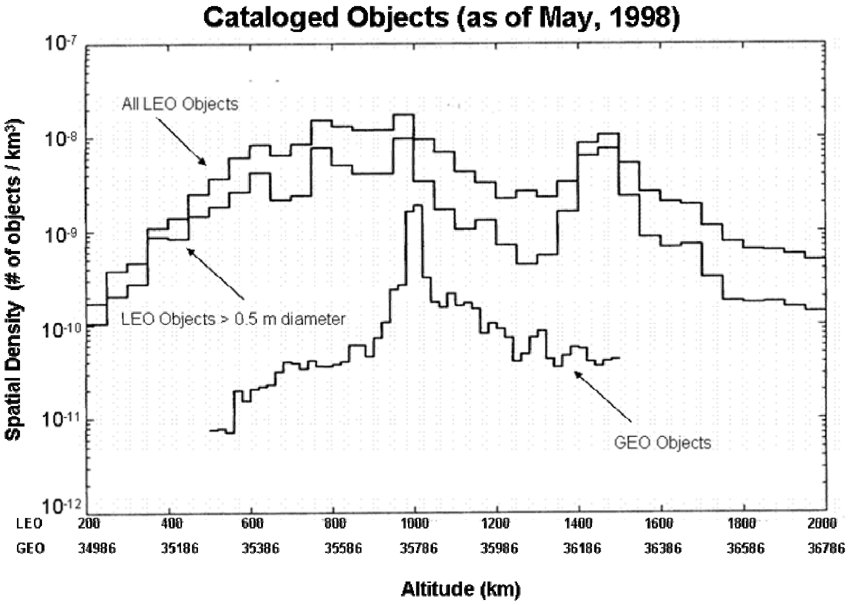

Figure 5.4, Spatial Density of Orbiting Objects[89]

Debris Reduction – Elimination – To increase the probability of survival of a space elevator, the number of large rocket bodies and dead satellites can be "controlled." This concept has at least three approaches:

- grab and de-orbit for low Earth orbiting large bodies
- grab and maneuver as needed for higher orbits
- grab and use GEO belt debris as GEO counterweight

The issue is similar in all cases, the inert body must be tracked, rendezvoused with, and captured prior to any action. Many designs have been proposed for this operation. A current concept is capture by a net that is "tossed" over the debris. The net would attach itself to the object/debris easily. The next step would be to stop the inert body's rotation in order to gain control for any action. To stop the

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[89] Larson, Wiley and James Wertz., *Space Mission Analysis and Design*. Ed. III, 2002, p. 843.

rotation, angular momentum must be minimized through an interaction with another force. One idea is to have large balloons (with torque rods) at the end of the ropes to add moment arms and drag. Once stabilized to a certain level, a long tether can be deployed to further stabilize and interact with the magnetic field lines of the Earth for de-orbit drag force creation. At LEO, the length of the tether can be relatively short (10s of km) for rapid decay while at MEO (middle Earth orbit) and GEO, longer tethers with weaker forces would result in longer times for desired outcomes. LEO bodies could be burned up; MEO bodies could be placed in space elevator compatible orbits for storage; while, GEO objects could be moved into a location where the mass can be changed from dangerous (crossing the space elevator vertical space corridor) to useful by making it part of a space elevator counterweight beyond GEO.

For smaller junk in orbit, many alternatives exist. These include:

- Energy exchange lasers that slow the junk down through "blow-off,"
- Sweepers picking up small things going in common direction, and,
- Bumper cars for exchange of momentum

To accomplish this task of elimination of junk in space, space nations could fund the clean-up similar to an environmental spill. If a space elevator is going to cost in the range of $10-40 billion, maybe a billion dollars could be put forth to clear-up space. How many entrepreneurs will surface when you explain that they can make $100 per kilogram for inert spacecraft or rocket body de-orbit, or movement to a stabilized orbit. This would be roughly 11,000 pieces for $1 billion. Two recent papers[90&91] discussed the concept of attaching to space objects and moving them.

Satellite Control – Knowledge – The current technology of radar and optical trackers (combined with older computers and software) leads to a situation where lack of knowledge of space debris is

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[90] Pearson, Jerome, Eugene Levin, John Oldson, Joseph Carrol, "The ElectroDynamic Delivery Experiment (EDDE)." Private Technical Paper. 2001.

[91] Ishige, Yuuki & Satorni Kawamoto. "Study on Electrodynamic Tether System for Space Debris Removal." (IAF-02-A.7.04.) 53rd International Astronautical Congress, 2002.

worrisome for space elevator designers. To apply techniques that could greatly enhance the safety of a space elevator, precise knowledge of the orbiting particles must be routine and continuous. New emphasis must be applied to better tracking (maybe even from platforms on a space elevator), computing, understanding, and prediction.

Satellite Control – Maneuver – As a space elevator is developed, new spacecraft should have non-threatening orbits, or, if necessary, maneuver around the vertical space corridor holding a space elevator. This would require a more robust propulsion system with the controls necessary to avoid the vertical space corridor.

Rules of the Road, Nodal Control – In addition to knowledge of where active spacecraft are, there should be a policy at the international level that mandates repetitive orbits well clear of a space elevator vertical space corridor. These are also called harmonic orbits because the periods of the orbits are divisible by an even number and have repeating equatorial node crossing. Most satellites have orbits near 90 minutes or 120 minutes or multiples of those numbers. With proper planning and execution, orbits can be arranged to have precise segments of the sidereal day. This would mean that these orbits would be able to repeat equatorial crossing and avoid the vertical corridor of a space elevator. This is the current policy at GEO (International Telecommunications Union (ITU) allocated slots) and could very easily be mandated for other orbits. One key is that most missions in space have multiple requirements that lead to orbital selection. By making equatorial crossings repetitive, to avoid a space elevator, an additional requirement in the design trade space, most missions would not be significantly effected.

Ribbon Motion – A space elevator can be moved from its natural position to avoid collisions. The risk of collision is real and, therefore, requires this capability as not all maneuvering can be mandated for debris. This motion could be modeled during the design phase to ensure that the dynamic stresses were included in the material selection and architecture.

Atmospheric Corridor Restrictions – The aero lift region must be recognized as an area where threats to fly, drive, or float into the ribbon's atmospheric corridor are restricted. To ensure integrity of the ribbon, flight rules, keep out zones, and guards will be required for security.

5.4.4 Systems Approach for Survival A systems approach for the evaluation of the survival of a space elevator enables the designers and backers to confidentially proceed with the research and development phase of the program. Even though the threat for space elevators is complex and multi-dimensional, designs are flexible across the spectrum of engineering and operations. This systems approach has the objective of minimizing the risk to the space elevator from meteors, meteorites and space debris. As such, the rest of the chapter shows a proposed prioritization of mitigation approaches for each altitude region.

Table 5.9 shows various approaches and sets a prioritization for a systems solution against debris, operational spacecraft, and meteors/meteorites. The order for the solution set is different for each altitude region because of the resultant system trades between region vs. threat vs. mitigation approach.

Super GEO

Priority # 1 Ribbon Design – The principle threat is micrometeorites. As such, a robust ribbon design solves most of the threat, ensuring survival through multiple hits per section per year enabling mission operation success.

Priority # 2 Rules of the Road – The future of Super GEO satellites is going to be significantly different with easy and cheap access to that altitude. As such, the movement of old satellites to graveyard orbits will change to one of capturing old satellites (and, perhaps, using their mass as counterweight).

Table 5.9, Systems Approach to Space Elevator Survival

Region	**Aero Lift**	**LEO**	**MA**	**GEO**	**S-GEO**
Kilometers	< 40	< 2,000	> 2,000 < 35,386	> 35,386 < 36186	>36,186
Threats	Planes, winds aloft, hurricanes, tornadoes, humans	Meteorites, Debris Density highest, Many inclinations & altitudes	Meteorite Less dense debris	Meteorites, slow interactions satellite debris	Meteorites
Methodology	**Priority**				
Ribbon Design	**3**	**1**	**1**	**2**	**1**
Ribbon Motion	**4**	**2**	**3**	**5**	
Debris Elimination		**4**	**4**	**1**	
Satellite Knowledge		**3**	**2**	**3**	
Rules of the Road	**2**	**5**	**5**	**4**	**2**
Corridor Protection	**1**				

GEO

Priority # 1 Debris Elimination – The largest threat is collision with a large spacecraft or rocket body and a space elevator. Collection of GEO satellites not under operational control could help significantly reduce the probability of collision. In addition, this collection of mass could aid in counter weighting for a space elevator.

Priority # 2 Ribbon Design – The meteorite threat is still significant and must be accounted for with ribbon design. Expectation of multiple hits per year will require a design robust enough to survive.

Priority # 3 Satellite Knowledge – The GEO arc is not very well tracked because of marginal optical resolution to 37,000 km and needs improvements to see if there are threats from smaller components of older satellites. Perhaps, an in orbit sensor could enhance our knowledge; and/or, a sensor located on a space elevator.

Priority # 4 Rules of the Road – Strengthen the GEO ITU rules to ensure no lost satellites or out of control inert bodies. Table 5.10 shows current orbital practices from 1997-2002, with only partial success at ensuring that satellites end up in this graveyard orbit. Only 22 satellites were in the appropriate drift orbits according to the International Agencies Debris Committee (IADC) report.

Priority # 5 Ribbon Motion – Dormant GEO satellites and high velocity GEO transfer orbit rocket bodies are large enough to sever the ribbon, but can be tracked, predicted, and avoided.

Table 5.10: GEO Re-orbiting Practices[92]

	1997	**1998**	**1999**	**2000**	**2001**	**Total**
Abandoned in GEO	5	8	6	5	6	**30**
Drift Orbit (too low perigee)	5	6	2	4	6	**23**
Appropriate Drift Orbit (IADC data)	7	7	4	2	2	**22**
Total	**17**	**21**	**12**	**11**	**14**	**75**

MA

Priority # 1 Ribbon Design – As the MEO region starts just above LEO, and also has a large set of human made debris in the 12 hour orbit, the ability to survive space debris off rocket bodies and spacecraft must be considered.

Priority # 2 Satellite Knowledge – As in the total area of space debris, better understanding of threats is important and can lead to better operational approaches to mitigate them.

Priority # 3 Ribbon Motion – Dormant navigation satellites and high velocity GEO transfer orbit rocket bodies are large enough to sever the ribbon, but can be tracked, predicted, and avoided.

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[92] Hussey, John, ed., Position Paper on Space Debris Mitigation Guidelines for Spacecraft, Draft – International Academy of Astronautics, 2003.

Priority # 4 Debris Elimination – Larger pieces of debris in highly elliptical orbits, such as the GEO transfer orbit, are indeed a threat and can be de-orbited relatively easily by using atmospheric drag at perigee.

Priority # 5 Rules of the Road – The MEO orbit is very important for today's navigation systems. As such, there will be multiple constellations at the "half way to GEO" location and large satellites must be controlled as harmonic orbits so they do not cross the equator at the precise location of the space elevator.

LEO

Priority # 1 Ribbon Design – Space engineers must assume that a ribbon will be impacted by small space debris and meteorites. As such, the design of a ribbon must be flexible enough to accept monthly (or weekly) hits and still be robust enough to function for its estimated lifetime of 50 years. The design of a ribbon can provide this capability through multiple strands of nanotubes, weave patterns, etc., maximizing longevity under these conditions.

Priority # 2 Ribbon Motion – This combines with situational awareness to enable operational success. One key element in the concept is multiple base legs that can move the bottom of a single strand elevator by simply changing the length of each leg. The dynamics of space elevator motion can be predicted and incorporated with satellite location knowledge to assist in moving out of the way of large space debris items.

Priority # 3 Satellite Knowledge – Operational approaches must be implemented for a set of debris mitigation techniques. By knowing the orbits of large space debris, a space elevator can be moved as required. To accomplish this, the precise orbital characteristics of space objects must be known.

Priority # 4 Debris Elimination – This concept is an idea whose time has come. We must not only stop polluting our environment, but we must ensure a healthy one. This could very well be construed as a "environmental cleanup" activity.

Priority # 5 Rules of the Road – The reality is that LEO satellites will be a staple of nations' missions and will be circling the globe every 100 minutes or so. An extra requirement in the systems design set should lead to orbits that are periodic. As such, they could avoid the space elevator nodal location. An international Rules of the

Road agreement can ensure that mission essential orbits can still be utilized, while maintaining a safe space elevator corridor.

Aero Lift

Priority # 1 Corridor Protection – Rules of the Road for flights, boating, and driving will ensure that the corridor does not suffer from accidental collisions.

Priority #2 Rules of the Road – This is an extension of priority #1, but applied to the international arena similar to maritime law or aeronautical treaties.

Priority #3 Ribbon Design – The ribbon must be designed for this unique transition from vacuum to sea level pressure. This transition through the various levels of atmospheric pressure will be dynamic and stressful on the ribbon. However, the ribbon must be manufactured with the stated objective of "no failures" in whatever environment it is in.

Priority #4 Ribbon Motion – This mitigation technique will be utilized when there is a predictable hazard that can be defeated by moving the ribbon legs across the surface of the Earth.

5.5 Select a Baseline

As a space elevator concept is strengthened by solid engineering and discussions are initiated over who will build what portions of the project, serious consideration and important engineering steps could be started. Selection of an open element baseline should include the previous analysis and robustly incorporate all the risk mitigation techniques. However, three timely initiatives are required for this systems approach:

- Initiate "rules of the road" discussions
- Initiate a de-orbit capability
- Enhance "zero debris" position

Initiate "Rules of the Road" Discussions: As a space elevator project goes forward, space nations must recognize that it will not remain under regulated in space. Rules must be initiated that would enable a space elevator vertical corridor to exist. Control of nodal passing must be implemented around the world with a mature set of rules ensuring that a space elevator becomes reality.

Initiate a De-Orbit Capability: Many papers and engineering concepts have surfaced that deal with elimination of current and future orbital debris. However, cost has always limited the activities to studies without follow-on engineering orbital tests. As a space elevator is funded and goes forward, investment in environmental cleanup should be included in all planning and funding requirements. An idea to initiate action could be to create a prize for the first organization to de-orbit a rocket body with a current estimated lifetime of ten years or more. The prize could be called the "Space Debris Enterprise Award." In addition, follow-up action must be stimulated with rewards for de-orbiting debris that is hazardous to the future of space elevators. New debris must become at least as socially, and perhaps legally, unacceptable as is terrestrial pollution.

Enhance a "Zero Debris" Position: Currently (2005) the International Academy of Astronautics is publishing a position paper on space debris.[93] In that paper the Academy takes the position that it is the goal of all space faring nations to create zero space debris within the three important regions. The LEO, navigation constellation ring, and GEO belt are identified. To ensure a healthy space elevator, the concept must be broadened to include all orbits. The mandatory implementation of Zero Debris Requirements would be early in a space systems design for programs with Preliminary Design Reviews after 2007. However, the positive impact on a space elevator and other future initiatives would be tremendous.

The final conclusion of a systems analysis for a space elevator that will survive debris, operational spacecraft, meteors and meteorites is:

Start the Initiatives
NOW !

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[93] Hussey, John ed., *Paper on Space Debris Mitigation Guidelines for Spacecraft, Draft* – International Academy of Astronautics, 2003.

5.6 Verify Baseline Meets Requirements

The application of the risk mitigation techniques to the space elevator baseline will ensure stakeholder, investor, and builder will feel more confident in the long term viability of the engineering. The following chart (Table 5.11 Requirements Fulfillment) compares requirements with risk mitigation techniques.

5.7 Iterate Process through the Lower Level Trades

As this is a preliminary look at the space elevator, confirmation is left to a later trade study after more analysis.

Table 5.11, Requirements Fulfillment Matrix

Basic	Detailed	Remedial Techniques
Zero Sever	No sever of total space elevator	All approaches mentioned
	Low occurrences of lightning	Design
	No explosions on ribbon	Design, Cor,
	Low occurrences of high winds/hurricanes	Dsg, Mnvr
	Laser power support not melt ribbon	Design, Dsg,
	No orbit/fly/float/drive within the space elevator corridor	Pol, Mnvr, Motn, Cor
	Debris/meteorites tracked and predicted	Kndg, Mnvr
	Robust ability to move ribbon from major space debris	Design, Kldg, Mnvr, Cor
	Ability to move ribbon from major spacecraft	Design, Kldg, Mnvr, Cor
Robust Ribbon	Safety factor of 2.5	Design, Mnvr,
	Cross strapping for backup	Design
	One-meter wide ribbon, curved	Design, Elm, Kldg, Mnvr
	Tolerance for Atomic Oxygen	Design
	Tolerance for bending modes	Design
	Tolerant to climber forces	Design
Robust Situational	Knowledge of solar/lunar effects (UV, 7 hour oscillation, radiation)	Design, Mot

Awareness	Tracking of satellite/rocket bodies	Kldg, Mnvr, Cor
	Tracking of space debris	Kldg, Mnvr, Cor
	Leadership in global debris mitigation efforts	Pol, Elm, Kldg, RoR
	International policy creator or enforcer	Pol, Elm, Kldg, RoR
	Enabler of debris reduction	Elm, Kldg

[Design -Ribbon Design; Pol-Debris Reduction, policy; Elm-Debris Reduction, elimination; Kldg-Satellite Control, knowledge; Mnvr-Satellite Control, maneuver; RoR-Rules of Road, nodal control; Motn-ribbon Motion; Cor-Atmospheric Corridor Restrictions]

CHAPTER VI – SYSTEMS ENGINEERING TRADE: ANCHOR INFRASTRUCTURE

6.0 Introduction

There is tremendous trade space open for the design of the lower 2,000 km of a space elevator. While the deployment phase will have the ribbon respond as a spacecraft with free ends and a center of mass, the Wright-Flyer and the mature space elevator will require a system attached to the Earth. The mature space elevator will have many options that will enhance its survivability and economics. The Wright-Flyer will have high survivability, but will start with the single ribbon to initiate the commercial aspects of the business. There are many questions and issues that must be addressed to enable a final design to be developed for the anchor infrastructure. As discussed in the chapter on systems engineering, the following tasks must be undertaken for a trade space analysis (as demonstrated in each section of this chapter). The results from the analysis presented in this chapter are preliminary and will only help the mega-project leaders to establish the questions to be studied in further analyses.

Table 6.1, Systems Engineering Process Tasks

	Systems Engineering Process Task	**Section**
1	Define the System Objectives (User's Needs)	**6.1**
2	Establish the Functionality (Functional Analysis)	**6.2**
3	Establish Performance Requirements (Requirements Analysis)	**6.3**
4	Evolve Design and Operations Concepts (Architecture Synthesis)	**6.4**
5	Select a Baseline (Cost/Benefit Trades)	**6.5**

6	Verify the Baseline Meets Requirements (User's Needs)	**6.6**
7	Iterate the Process through Lower Level Trades (Decomposition)	**6.7**

These tasks will be stepped through to apply systems engineering process to the analysis of a base leg infrastructure. There are two basic questions that must be addressed when designing the lower portion of a space elevator. These questions deal with the full life cycle of the space elevator mega-project, but focus on the Wright-Flyer phase.

- Can the anchor be off zero latitude?
- Should the anchor be located on land or at sea?

The trade space results are summarized at the end of the chapter in the Requirements Fulfillment Matrix (Table 6.5).

6.1 User Needs – System Objectives

The anchor location and lower portion of the space elevator will be designed with many factors included in the trade space. Some of the anticipated desires of the customers and users are:

- Safety
- Located at the Equator or a low latitude line (the movement off the
- equator effects the space elevator loading payload weight capability)
- Easy logistics (the operations phase must be designed early)
- Politically stable
- Interoperable (standards are set in the transportation infrastructure allowing conforming manufacturers to build climbers for the basic design)

6.2 Establish Functionality

This task leads to an analysis that is closely tied to operations. The customer needs of interoperability and safety will drive the design from the beginning. Functionality will be developed to a greater extent as the architecture is better defined.

6.3 Establish Performance Requirements

The basic requirements have been broken down into the customer needs and the resulting detailed requirements for the anchor infrastructure. The requirements are shown in Table 6.2.

6.4 Evolve Design and Operations Concepts

This portion of the systems engineering process evaluates critical trade spaces. The analysis follows, as the basing infrastructure has been discussed, with two questions:

- Can the anchor be off zero latitude?
- Should the anchor be located on land or at sea?

Table 6.2, Performance Requirements

Basic	Detailed
Safe Operations	No catastrophic sever of space elevator
	No loss of climbers off ribbon
	Ribbon survival against multiple small debris hits per meter per year
	No explosions on ribbon
	Safe laser power support
	Laser power support not melt ribbon
	No orbit/fly/float/drive within the space elevator corridor
	Debris/meteorites tracked and predicted
	Robust ability to move ribbon from major space debris
	Ability to move ribbon from major spacecraft
	Inspector/repair climber infrastructure
	Low occurrences of lightning

	Low occurrences of high winds/hurricanes
Lower Latitude	Low percentage of cloud cover
	High payload mass capable space elevator
	Ocean basing
	Flexible location anchoring
	Large area open for base leg infrastructure
Easy Logistics	Existing transportation infrastructure
	Comfortable living facilities for operators
	Open area for logistics support
Politically Stable	International waters
	Country stability
	21st century political approach
Interoperable	Ribbon design acceptable to all climbers (standards based)
	Easy interface with transportation infrastructure
	Central location of anchor infrastructure
	Local support for logistics
	Easy support for science investigation (vertical emplacement)

6.4.1 Latitude Allowance Over the short history of the engineering design for a space elevator, the assumption has most often been that the terrestrial end must be at zero latitude. This has been coupled with the idea that the nadir point of the geosynchronous location is essential for stability. Further analysis leads one to believe that the initial "grounding" of the long ribbon at the end of the deployment phase must be at that nadir location; however, once the Wright-Flyer is initiated, the basic location can move off the equator. The preliminary answer from early analysis seems to be a movable anchor off nadir, with the appropriate compensation for the total space elevator beyond the GEO location.[94] This capability could provide flexibility to the location of the anchor station and could allow dynamic coupling to negate natural modes of motion. However, the question requires a large simulation that incorporates each element of the space elevator, all the masses attached to the ribbon (hotels/nodes/logistic centers), and of course all the moving climbers. This question is a second level issue until the anchor basing options are refined to a more precise level. This book assumes a location on the equator for the major anchor point of the base leg segment, with the option of future locations off nadir.

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[94] Gassend, Blaise. "Non-Equatorial Uniform-Stress Space Elevator," 3rd Annual International Space Elevator Conference, Washington DC, June 20, 2004.

6.4.1.1 Why "off latitude"? The assumption has always been to just run the ribbon down to the equator. As the studies have come to the conclusion that there is potential flexibility to the location of the anchor, the question must surface and be answered as to why move off the zero latitude location. Here are three good reasons.

- Better location for anchor: Flexibility in choosing the base leg location would enable the design team to pick islands, areas of ocean without currents, or politically wise locations.
- Move ribbon out of radiation belts: The passage through the radiation belts will be one of the major hazards to both humans and robotic equipment. As such, reduction of the time inside these belts would assist in the safety and operations of the system.
- Move ribbon for defensive purposes: Placing the ribbon upon soil owned by certain countries would enable more security. Placing the ribbon in the middle of an open ocean area would enable protection to be well defined and broadcast to the public.

6.4.1.2 Trade off: Equation Showing Effects There is an equation that relates climber capacity levels versus the latitude of the base leg.[95] This relationship is a cosine function as reflected in Figure 6.1(relating value of being off-nadir vs. cost of achieving north/south latitude locations). The payload capacity is shown as a percentage with respect to the baseline Wright-Flyer at the equator. An exact goodness factor must be developed and shown to give the designers a feel for the potential range of deployments off of the equator.

6.4.2 Land or Sea Based The analysis of this question results in trades crossing both management and engineering disciplines. Both of these areas are addressed below with trades identified; however, the final design consideration will be influenced by the stakeholders and financers. The space elevator systems architect must ensure that all factors are considered to include items that do not influence engineering designs, because these could dominate. A likely determinate for location will be input by the financial investors and their percieved return on investment.

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[95] Ibed.

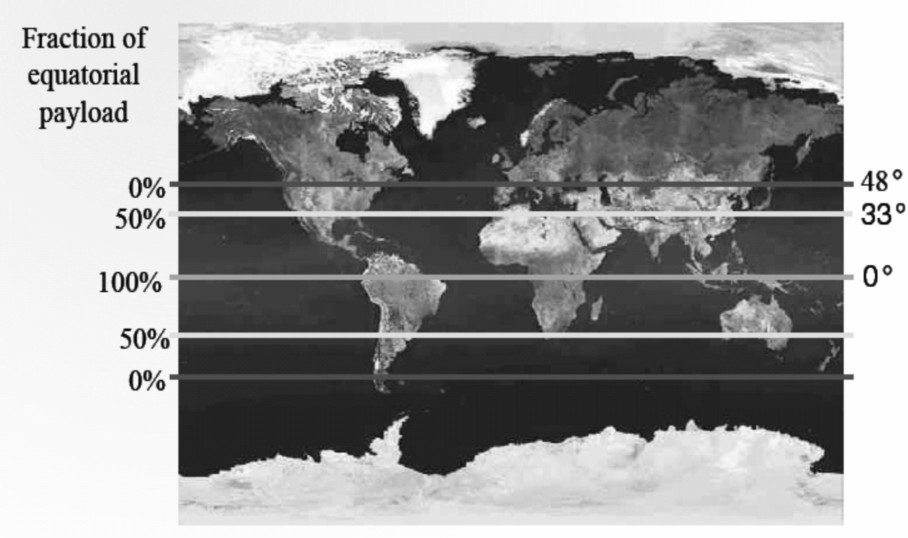

Figure 6.1, Payload Mass vs. Latitude North/South[96]

6.4.2.1 Land Based Option Early science fiction with the space elevator based the anchor at the top of a tall mountain which would enable the team to start the trip at a higher altitude, further from Earth's center of gravity. The anchor could easily be tied to the ground so that the base would not move. There are several mountain tops close to the equator that could be a base location. The advantages are leveraged from the attribute of high altitude starting location vs. the difficulties of working at the altitude in the cold, with major weather periods, and immature transportation infrastructure.

6.4.2.2 Sea Based Option An idea similar to the land based anchor is a sea based floating anchor infrastructure. The strengths are based around the heritage of the sea with its own laws and history of political insulation. In addition, a background exists for sea based infrastructure with logistics strengths for long distance transportation, simplicity, and proven technologies. There are expanses of the ocean that are open and usable with minimal impact to current human endeavors. Joseph Gardner presented a solid answer to the question of "where at sea" at the Second Annual International Space Elevator Conference. He showed that there was a location 2000 km west of

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[96] Gardner, Joseph. "Where on Earth? Chosing an Anchor Point," 2nd Annual International Space Elevator Conference, Sante Fe, NM. Oct 2003.

Ecuador that had favorable characteristics; one lightening strike per year per square kilometer (Figure 6.2), very low probability of hurricanes and cyclones, and almost no wave issues. In addition, there are locations in this region that have very high percentage of cloud-free days for efficient laser power transmission (as shown in Figure 6-3).

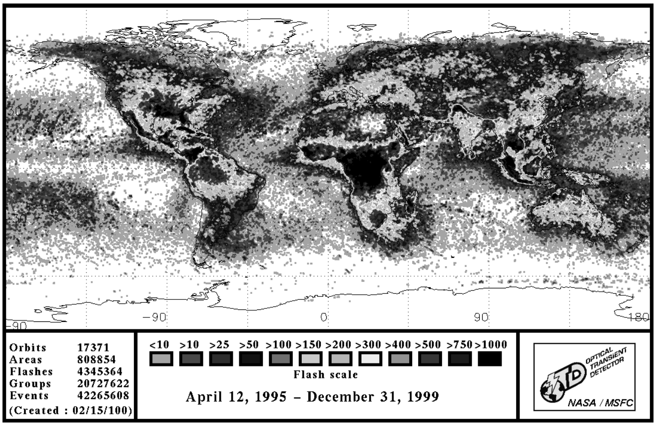

Figure 6-2, Lightning Rate Image[97]

6.4.2.3 Trade Space for Anchor Location Table 6.3 shows the trade matrix comparing land and sea based alternatives. This analysis looks at the management side of the issue as well as the engineering side. The breakouts cover sovereignty issues, personnel issues, engineering issues and, especially, risk trades. Table 6.3 leads one to the conclusion that operating in a hostile environment, like a top of a mountain, has major disadvantages while operating in a quiescent ocean area lends itself to leveraging the heritage of sea based transportation and logistics. One interesting option would be the combination of land based and sea based to leverage the strengths of both options.

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[97] Edwards, Bradley C. and Eric A. Westling, *The Space Elevator,* BC Edwards, Houston, Tx, 2003, p. 106.

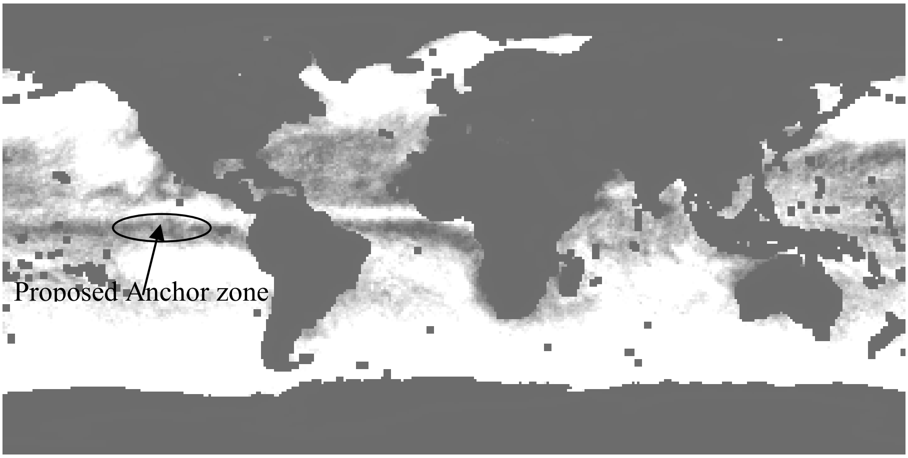

Table 6.3, Anchor Locations – Sea vs. Land

	Land Based	**Sea Based**
Management		
Sovereign Country vs. Law of Sea	Laws of Nations Sovereign rights Ownership Influence Minimizes International control Access control to project Political upheaval	International Laws of the Sea Adapt oil platforms Large open areas Traditional logistics simplicity (ships and tugs)
Personal Issues	Passports Local laws Local customs Languages Nationalization	Freedom of access Work permits easy Work rules dominate Project focus infrastructure
Engineering		
Top of Mountain vs. Sea Surface	Access issues Road/railroad to top Support infrastructure Weather problems	Open area (400 km radius) Easy movement Ship anchors proven Engineering history (ships)

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[98] Edwards, Bradley C. and Eric A. Westling, *The Space Elevator,* BC Edwards, Houston, Tx, 2003, p. 64.

		Quiescent weather patterns (2000 km west of Ecuador)
Risk	No local personnel	Open areas for damage control
Anchor	Every mountain different	Anchor ties easily to huge ship
Duplication	Transportation infrastructure varies	Transportation easy

6.4.3 Factors for Anchor Most past discussions have assumed a single ribbon stretched from an anchor to a space elevator centered at GEO for an Earth based bridge to the stars. Indeed, the deployment and early Wright-Flyer phases of a space elevator will have a single ribbon attached to the Earth at the equator.

The Wright-Flyer anchor will have many requirements leading to a development program and eventually a base station. Two major items have surfaced during the analysis; flexibility in location and massive anchor infrastructure support at the terminal end. Each of these will stimulate much discussion prior to project initiation.

Location flexibility is derived from the recognition that survivability of a space elevator is paramount and must be ensured through design, development and operational procedures. The ability to move an anchor leads one toward a sea based option with the natural location flexibility of large ships or floating platforms.

The size of an anchor station seems to be growing as the project progresses. The idea of continuous operations with launches on a five carriers per week schedule implies that the anchor infrastructure supports:

- Space elevator cable attachment
- Mass necessary to hold space elevator in place
- An operations center
- Room for cargo and carriers ready for flight
- Room for just returned cargo and carriers
- Room for repair of cargo or carriers
- Personnel housing

- Personnel support infrastructure
- Laser power infrastructure
- Communications infrastructure

These two principle requirements for an anchor infrastructure seem to be driving factors in the design process. As one addresses the trades for this issue, an aircraft carrier solution becomes compelling. The addition of mass required to produce the above infrastructure would hold the pull of the space elevator while the room available for infrastructure support and personnel should be sufficient.

6.5 Select a Potential Baseline Architecture

For the earth terminus of the space elevator, various factors contribute to the analysis. The need for a free space of circular shape around the anchor infrastructure; the need to interface with terrestrial transportation; and, the political freedom afforded to international endeavors could lead the decision toward an anchor architecture that is sea based. Many studies have been conducted looking for the proper placement along the equator. Future studies must be conducted to pinpoint the location and analyze the orbital dynamics issues at that longitude. Therefore, a recommended answer from this analysis could lead to a placement along the equator, west of Ecuador, within a radius of 400 km from a center terminus - perhaps centered upon an island.

6.6 Verify Baseline Meets Requirements

The following table (6.5) lists the requirements and the verification details and approaches.

6.7 Iterate Process through Lower Trade Studies

As this is a preliminary look at the space elevator, confirmation is left to a later trade study after more analysis. This has not been a complete systems study or trade of the complete issue of where to place the anchor. A full systems study and complete tradeoff must include studies of failure modes, launch performance, deployment scenarios, construction aspects and operational costs.

Table 6.4, Requirements Fulfillment Matrix

Basic	Detailed	Low Latitude	Sea–Land
Safe Operations	No sever of total space elevator	+	S
	No loss of climbers off ribbon	+	
	No explosions on ribbon		
	Laser power support safe		L
	Laser power support not melt ribbon		
	No orbit/fly/float/drive within the space elevator corridor	+	S
	Debris/meteorites tracked and predicted		
	Robust ability to move ribbon from major space debris	+	S
	Ability to move ribbon from major spacecraft	+	S
	Inspector/repair climber infrastructure	+	
	Low occurrences of lightning		S
	Low occurrences of high winds/hurricanes		S
Lower Latitude	Low percentage of cloud cover	+	S
	High mass capable space elevator		
	Ocean basing	+	S
	Flexible location anchoring	+	S
	Large area open for anchor infrastructure	+	S
Easy Logistics	Existing transportation infrastructure	+	S
	Comfortable living facilities for operators	+	S
	Open area for logistics support	+	S
Politically Stable	International waters	+	S
	Country stability	+	L
	21st century political approach	+	S

Interoperable	Ribbon design accessible to all climbers (standards based)		
	Easy interface with transportation infrastructure	+	S
	Central location of anchor infrastructure	+	S
	Local support for logistics	+	S
	Easy support for science investigation	+	

[S=sea advantage, L=land advantage; + = low Latitude advantages]

CHAPTER VII – SYSTEMS ENGINEERING TRADE: OPERATIONS

7.0 Introduction[99]

Early introduction of users' expertise to the design process will enhance the operability of the total mega-project. Smooth work flow, high reliability, low costs, and satisfied customers lead to a successful business with fewer conflicts and issues. As such, an early look at systems operations using a systems engineering approach will greatly enhance the day-to-day operations of a space elevator business venture. As discussed in the chapter on systems engineering, the following tasks must be accomplished to lay out the plans and processes for any mega-project.

Table 7.1, Systems Engineering Process Tasks

	Systems Engineering Process Task	Section
1	Define the System Objectives (User's Needs)	**7.1**
2	Establish the Functionality (Functional Analysis)	**7.2**
3	Establish Performance Requirements (Requirements Analysis)	**7.3**
4	Evolve Design and Operations Concepts (Architecture Synthesis)	**7.4**
5	Select a Baseline (Cost/Benefit Trades)	**7.5**
6	Verify the Baseline Meets Requirements (User's Needs)	**7.6**
7	Iterate the Process through Lower Level Trades (Decomposition)	**7.7**

This chapter will step through these systems engineering tasks to initiate the discussion on system level operations. It is essential that

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[99] Westling, Eric. Personal communications supported chapter. 2005.

the guidelines of simple, reliable and cost effective be the mantra of design engineers, especially when developing basic operational concepts. When dealing with traditional spacecraft operations, the development time scale has been shown to be long (10 to 15 years) while involvement of operators usually occurs late in the process, as shown by Table 7.2.

Table 7.2, Traditional Space Operations Timelines[100]

Pre-launch & Launch	**Early Orbit Checkout**	**Normal Operations**
	2 Days – 6 Months	**Several Weeks – 30 Years**
1 – 2 Years • Develop flight plan - Spacecraft - Payload - Ground system • Develop training plan • Identify simulator requirements • Integrate and test support systems **6 Months** • Assemble operations team • Validate ground-system database • Validate ground-system hardware • Validate flight software **3 Months** • Start pre-launch training • Rehearse launch • Demonstrate communications protocol **1 Month** • Simulate launch operations • Review readiness	• Validate components • Validate subsystems • Validate subsystem interfaces • Validate systems • Detect and analyze anomalies • Calibrate instruments • Validate instrument processing • Validate protocol for external interfaces • Maneuver spacecraft to mission orbit	• Perform real-time spacecraft operations • Process and distribute payload data • Translate requirements into operational activities • Resolve anomalies • Maintain ground-system database • Maintain flight software • Maintain ground software • Continue operator training • Recover and repair spacecraft • Dispose of non-operational spacecraft

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[100] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.

Launch • Support launch team • Transfer spacecraft to initial orbit		

The delay of involvement of mission operations expertise until late in the development process has been a basic flaw in designing space systems. Design engineers start their conceptual development 8 to 10 years prior to launch with requirements solidification for space systems design at the systems requirements review, usually 7 years prior to launch. This leads to the logical conclusion that inputs from operators are not established in a timely manner for space systems development. This becomes even more critical when one realizes most systems are operational for more than 10 years and have a disproportionate share of funding in the out-years covering operations, as shown in Figure 7.1.

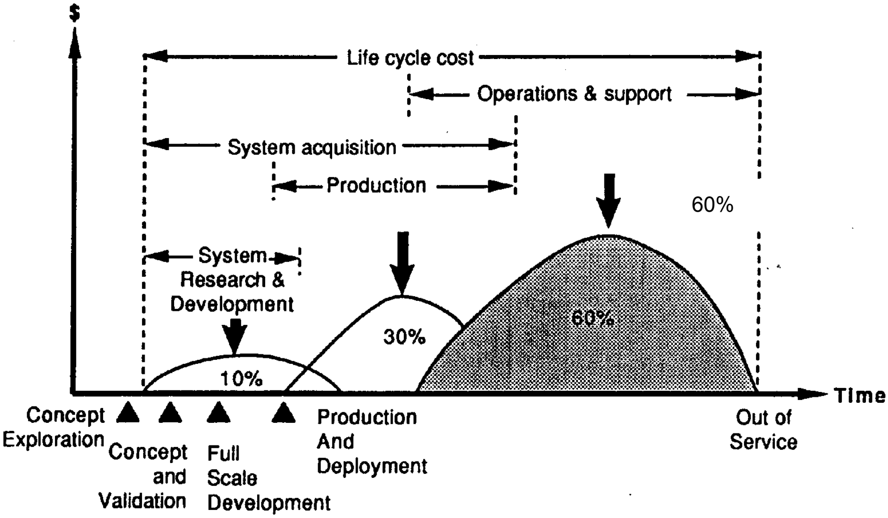

Figure 7.1, Lifecycle Costs[101]

To resolve this lack of timely inputs from operators, early involvement in developing requirements for operations must be established. Mission operators must be invited to contribute toward a space elevator design prior to finalization of requirements. The

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[101] Larson, Wiley and James Wertz, *Space Mission Analysis and Design*, Microcosm Press, 1999.

simple insertion of automation to cover day-to-day tasking (only understood by space operators) could save manpower, and hence, out-year dollars. This concept is described by Boden in *Cost Effective Space Mission Operations*[102]. Figure 7.2 shows how the flow of a normal operations activity occurs (top box) reflecting historic mega-project acquisition. The series of boxes (added below the acquisition process) is a systems engineering approach to operational design. It starts with a Mission Operations Concept that feeds the acquisition process and enables operators' "good ideas" to be included during the requirements development phase.

7.1 User Needs – System Objectives

The overall goal for the Wright-Flyer space elevator is to conduct operations with a 20 ton payload capability with five payloads on the ribbon at any one time. The movement to the mature space elevator phase with human cargo will incorporate movement of 200 ton payload capability. This chapter focuses on establishing an operations concept for the Wright-Flyer. The goals are:

- 20 ton payload capability
- 5 climbers with payload at any instant (surface to GEO)
- Climbers estimated at 20 tons each
- $100 per kilogram (when multiple Wright-Flyers operate)
- Reliability of elevator (777 jet engine exceeds 17,000 hours)[103]

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[102] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.

[103] Schmitt, Capt. John H., personal communications. 9/18/2003.

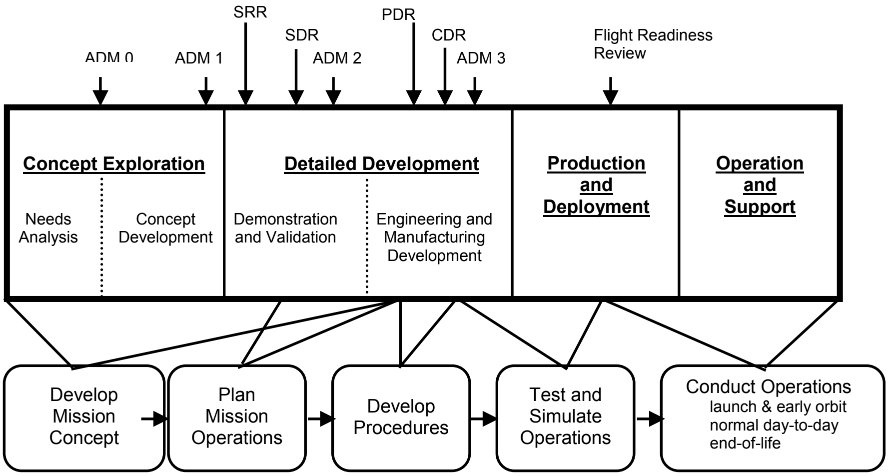

Figure 7.2, Acquisition Flow with Operations Inputs[104]

ADM – Acquisition Decision Memorandum CDR – Critical Design Review

PDR – Preliminary Design Review SDR – System Definition Review

SRR – System Requirements Review

7.2 Establish Functionality

7.2.1 Work Flow The work flow, along organizational lines, for the Wright-Flyer would look something like the following:

Business and Support Organization

Business Operations [Headquarters responsible for controlling the payload financing] – sells missions, schedules deliveries, collects payments, customer service, supportive administration, and accounting.

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[104] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.

Receiving – shipping and receiving terrestrial hardware [on-site acceptance and shipping] payloads and support infrastructure, docking facilities, and storage and handling (cargo and people).

Facility Operations – maintains, improves, sea-air-land surveillance, sea-air-land protection, personnel safety/care/feeding/housing, and power management.

Mission Crew Organizations

Payload Preparation - pre-launch servicing, payload assembly, and climber loading and unloading

Space Elevator Ribbon Operations - repair & maintenance, launch of climbers, transport to destination, off-load, communications and computers, ribbon tracking, collision avoidance, and ribbon movement.

Spacecraft Operations (off space elevator assets) – tracking, command and control, launch vehicle control and ribbon protection.

Operations Center – command and control, ribbon traffic monitoring, power beaming, debris monitoring, scheduling, administration and personnel.

7.2.2 Operations Center Boden, in *Cost Effective Space Mission Operations* provided the first academic approach to a space operations center. Figure 10.3 shows the layout given by this initial look at systems engineering process assessment for operations.

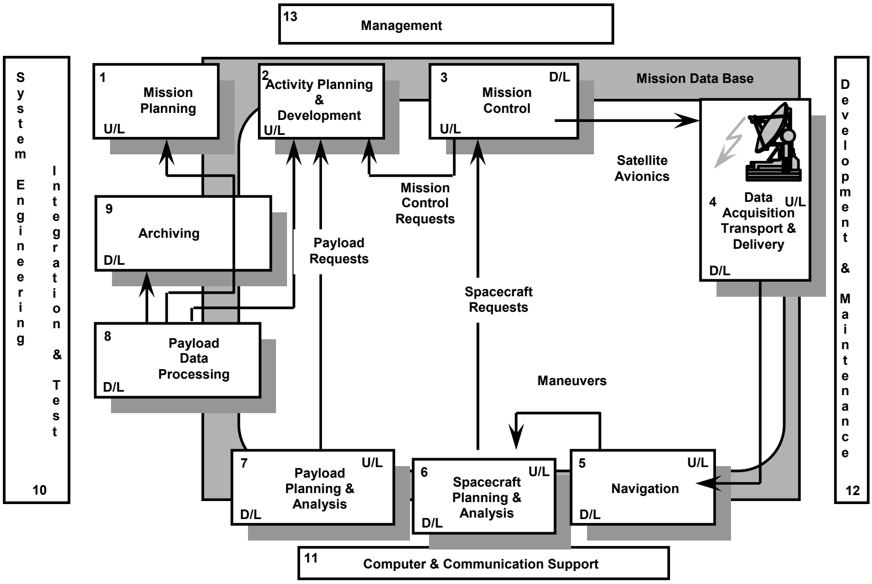

Figure 7.3, Space Operations Functions[105]

If we substitute space elevator operations for spacecraft operations, the figure applies directly to the Wright-Flyer space elevator. The functions and their descriptions are listed in Table 7.3.

Table 7.3, Space Elevator Mission Operations Functions[106]

Function	Description
1. Mission Planning	Quantify mission objectives and goals, define payload & operational characteristics, define mission phases, identify mission rules, and define climber characteristics, maintain positive mission margins, examine and trade autonomy, evaluate numbers and complexity of mission / flight rules, identify objectives and goals.
2. Activity Planning and Development	Define the activities, generate and iterate activities, check the mission / flight rules, generate timelines, validate activities, and translate activities.

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[105] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.
[106] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.

3. Mission Control	Develop procedures for controllers, support integration and test, configure ground support, transmit commands to climbers, monitor health and safety, schedule tracking support, support planning teams.
4. Data Transport & Delivery	Validate each data handling ability, send commands to space elevator climbers, manage data flow, determine data quality, continuity and completeness.
5. Navigation & Orbit Control	Support pre-launch mission planning, determine ascension plans, design analyze transportation profile, monitor and re-calculate issues as climber ascends.
6. Climbers Operations	Plan climber profile, assess loading characteristics, operate and maintain control during ascent / decent, maintain flight software, and analyze engineering issues.
7. Payload Operations	Plan payload positioning and ascent profile, calibrate the loading and center of mass, analyze hazardous issues, maintain climber software, and publish climber status.
8. Data Processing	Validate processing system, generate data records across space elevator, process sensor specific date, correlate ancillary data, generate reports, and manage data.
9. Archiving & Maintaining the Mission Database	Manage and retrieve data, secure data bases, notify users of data transport, archive data sets, and maintain and analyze operations data in real time.
10. System Engineering and Integration & Test	Maintain systems architecture, generate and review control requirements, define and document control interfaces, monitor standards, simulate / test and train people for mission, and evaluate system periodically.
11. Computer & Communications Support	Understand and maintain computer and networks across space elevator infrastructure, control network and hardware access, and monitor all functions.
12. Software Development and Maintenance	Understand basic requirements and their satisfaction, test and maintain old / new software, train new capabilities for new people, and ensure dependence on proper process.
13. Managing Mission Operations	Understand and maintain operations organization, hire, fire, manage interfaces, and manage schedule and risks.

7.3 Establish Performance Requirements

The basic requirements have been discussed and the goal of smooth operations is the objective. Table 7.4 shows the operational performance requirements for a space elevator.

Table 7.4, Operations Performance Requirements

Basic	Detailed
Simple Operations	Anchor location
	Not responsible for terrestrial delivery to/from space elevator
	Ribbon maintenance in parallel with operations
	Power generated locally
	Transportation infrastructure similar to historic approaches
	One business headquarters (off-site)
	One operations center (on-site)
Low Personnel Costs	Highly automated operations
	Small operations and maintenance crews
	Minimize human tasking
	Maximize robotic assistance
	Multiple paths for payloads to arrive
	Simple assembly area with established standards
	Highly automated operations
High Reliability	Greater than six sigma requirements
	Standards established early
	Automation check-out in simulations first

7.4 Evolve Design and Operations Concepts

In this section, the development of an operations process will be examined. The first step is to develop a mission operations concept. This is a document that specifies how the mission operations system (MOS) will meet mission objectives. It describes the attributes of the basic elements for a space elevator and how they work together. It provides derived requirements for the mission operations system and traceability to top-level mission requirements for a space elevator. It emphasizes areas where trades can be made to minimize lifecycle costs and get better information from and for the mission. The Mission Operations Concept also requires disparate disciplines to communicate with common words and processes. It assures that the operations organization provides a tested and certified mission operations system that meets requirements at reasonable cost. To develop a Mission Operations Concept, three components come together sequentially. The first is the development, early before the requirements have been solidified, of inputs to a refined process. The second is a refined process to create a Mission Operations Concept while the third is a set of usable information that can provide the mission team with finite and understandable concepts, timelines and options. These three components are shown in the following table.

Table 7.5, Mission Operations Concept Components[107]

Inputs	Process	Outputs
Mission Objective	Identify mission concept, architecture, and requirements	Operational scenarios
Mission Description	Determine required mission operations functions	Timelines
Mission Philosophies, strategies, & tactics	Identify options for performing functions	Data flow diagrams
Programmatic constraints	Do trades	Organization and team responsibilities
End-to-end information system characteristics	Develop operations scenarios for selected periods	Cost and complexity drivers for a given set of inputs
Ground systems characteristics	Develop timelines	Requirements and derived requirements
Payload characteristics & capabilities	Determine resources needed	Technology development plan
Climber characteristics	Develop data flow diagrams	
End-user data products	Characterize operations organizations and teams	
	Assess mission complexity, utility and cost drivers	

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[107] Boden, Daryl, Cost Effective Space Mission Operations, McGraw Hill, 1996.

	Identify derived requirements	
	Generate technology development plan	
	Document and iterate	

7.5 Select a Baseline

The baseline for the Wright-Flyer includes:

- A headquarters for business located off site
- An operations center on-site
- Work flow similar to historic transportation infrastructures

To better understand this preliminary operations concept, climber operations are expanded upon, as they will be the determining factor in overall infrastructure requirements for the anchor node and the ribbon design.

Climbers are rather large. The 20 ton climbers, by the current concept, are estimated to be 20m long, 10m wide and stand 15m high(3000 cubic meters, the equivalent of a 5 story house with 92 average size rooms). This impressive size immediately forces the design of anchor vessels. At a minimum, this size climber will need two rooms (22x12x17 m) with no interrupting structures for work flow activities; one for the actual launch-on-ribbon, open to the sky, and the other a ready room for the next climber in line. These are huge room requirements for any structure, let alone for a floating vessel. Actually, there will probably be a need for three such rooms, assembly-line fashion, to keep up with a busy launch schedule; the first to assemble a climber, the second to mount and ready the payload, and the third for launch. These rooms will need to be air-conditioned, and air-filtered. All other dealings with climbers will have to be in a disassembled state. Climbers should therefore be designed in modular form with quick disassembly-reassemble, like Indy race cars where, with a good pit crew, you can get tires changed in 12 seconds.

When a climber returns down the cable it would stop level with the outside deck rather than continuing lower into the launch bay. It would then be disconnected from the cable and, with a motorized dolly, moved off to the side, probably all the way to the far end of the ship. Here it would be knocked down to its primary smaller parts via quick releases at the critical points. Note that all wiring and connectors must also have quick disconnects at these sub-assembly boundaries. The sub-assemblies are now lowered below decks to begin their servicing and refurbishment journey.

Servicing, while hopefully automated, can be heavily assisted by power equipment. Set pieces with hydraulics designed to handle specific functions such as dismounting and mounting the electric motors or drive tracks. The estimate is that it would take one eight hour shift to service a climber (probably working in teams of two or three). Servicing would be pull-and-replace, no actual repairs below the component level would be done on-site. A large store of replacement parts would be maintained with used items loaded and returned for refurbishment, salvage or disposal, (along with shipping out the considerable volume of packing material generated by the incoming payloads).

There will likely be several sub-assembly service areas, one for each of the assemblies with tooling and power assists specific to that part (for example the motor train assembly). These workrooms can be of more normal size, similar to the service bays for heavy-duty trucks, about 5x8x4 m. Swing room for power assist and overhead lifts could move this out to 6x9x5 m. A set of storage rooms, sealed and climate controlled will be needed for the service finished sub-assemblies prior to being sent to the large assembly room[108]. After a trip to space and back – from 40,000 to 200,000 km – the climbers may be a bit tuckered out. The tracks or driving wheels will have to be inspected and/or replaced, as will parts of or all of the motor and drive-train. The rest will need, at the least, extensive inspection, testing and refurbishing. This implies, as above, a good deal of working space, support hardware and robust air-conditioning, in this case, with a resident work force of technicians and engineers. Some estimates of the size of ship needed to support the base operations exceed an aircraft carrier, thus ensuring feedback from marine design engineers.

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[108] For working areas and especially for ships, rooms need not have walls except for environment control. A room is really the space between load bearing supports, where partitions can be attached if needed, or the work area of machinery. Otherwise these can be conjoined areas for communication and movement.

7.6 Verify Baseline meets Requirements

The following table will show the requirements and verification that must be met.

Table 7.6, Requirements Fulfillment Matrix

Basic	Detailed	Satisfied?
Simple Operations	Anchor Location	Yes
	Not responsible for delivery to/from space elevator	Yes - assumption
	Ribbon maintenance in parallel with operations	Yes
	Power generated locally	Yes – trade study
	Transportation infrastructure similar to historic approaches	Yes - assumption
	One business headquarters (off-site)	Yes - logical
	One operations center (on-site)	Yes – current concept
Low Personnel Costs	Highly automated operations	Yes – set requirements
	Small operations and maintenance crews	Yes – major automation
	Minimize human tasking	Yes - automation
	Maximize robotic assistances	yes
	Multiple paths for payloads to arrive	Yes – conceptual flow
	Simple assembly area with established standards	Yes – conceptual flow
	Highly automated operations	Yes
High Reliability	Greater than six sigma requirements	Yes – set requirement
	Standards set early	Yes - assumption
	Automation check-out in simulations first	Yes - logical

7.7 Iterate Process through Lower Level Trade Studies

As this is a preliminary look at a space elevator, confirmation of these operational concepts is left to a later trade study after more analyses. As this is the initial pass through a space elevator operations concept for the Wright-Flyer, there will be many more iterations prior to start of commercial revenue.

CHAPTER VIII – TO THE MOON: A VISIONARY ARCHITECTURE[109]

8.1 Introduction

In this book we have looked at a space elevator from the big picture view (Space Systems Architecture) and the technical detail view (Space Systems Engineering). This chapter extends beyond the current analysis and provides a preview of what "could be!" The visionary architecture of lunar infrastructure leverages the tremendous strengths of a space elevator for not only ease of operations, but tremendous cost savings. This lunar exploration program could be enabled through the use of a space elevator. This work is based directly upon a proposal[110] submitted in response to a NASA Broad Area Announcement for concept development. The concept lays out a plan for construction of a lunar base with a crew of at least eight people and allows for dramatic expansion and development into the rest of the solar system. The basic approach relies upon a space elevator for the majority of the lift requirements with human-rated rockets for the astronauts/cosmonauts/tiakonauts. The cost of exploration programs proposed by U.S. President Bush (lunar base, Mars base and solar system exploration) can be completed for $120B when a space elevator is utilized (estimate from BAA 04-01). For comparison, a rocket based program could cost ~$500B. A space elevator program also has greatly reduced risk, increased redundancy, excess launch capacity, likelihood to become self-sufficient and direct

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[109] Inputs for this chapter were derived (with significant re-use approval) from Dr. Edwards -: Edwards, Bradley C. and Ben Shelef, "The Space Elevator and NASA's New Space Initiative," International Astronautical Congress, Vancouver, Oct. 2004, and
Ewards, Bradley C., "Space Elevator-Based Program for Lunar Exploration," BAA 04-01 – Concept Exploration and Refinement to NASA, July 16, 2004.[additional authors were Dr. Paul Spudis, Dr. Heinz-Hermann Koelle, Dr. Michael Duke, Ms. Pamela Luskin, Ms. Patricia Russell, Dr. Hyam Benaroya, Dr. David Raitt, Mr. Ben Shelef, & Dr. Bryan Laubscher]

[110] Ibid.

application to investigating the remainder of the solar system. In addition, a space elevator would essentially eliminate the historic mass restrictions so entwined into space systems design philosophies. Table 8.1 compares the strengths of the current NASA launch concept to the space elevator approach for journeys beyond low Earth orbit.

Table 8.1, Enablers for Space Elevator-based Exploration Program

Aspect	Space Elevator Strength	Current NASA Concept
Cost Estimate	$120 B (US)	$500 B (US)
Infrastructure	Permanent, continuous	Repetitive Rockets
	Inexpensive operations	Rocket based operations
	Reasonable size payloads	Fairing based payloads
	Minimum stress	Rock/Roll of launch
Human Rating	Next generation space elevator	All rockets
	(initially use rockets to launch humans)	

8.1.1 The Exploration Vision On January 14, 2004, U. S. President George W. Bush articulated a new vision for space exploration, "A Renewed Spirit of Discovery." In February 2004, NASA released "The Vision for Space Exploration," a committed approach to answer the President's call. As articulated:[111]

> *The fundamental goal of this vision is to advance U. S. scientific, security, and economic interest through a robust space exploration program.*
>
> > *(1) Implement a sustained and affordable human and robotic program to explore the solar system and beyond.*
> >
> > *(2) Extend human presence across the solar system, starting with a human return to the moon by the year 2020, in preparation for human exploration of Mars and other destinations.*

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[111] "The Vision for Space Exploration," NASA release, February 2004.

> *(3) Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and promote international and commercial participation in exploration to further U. S. scientific, security, and economic interests.*

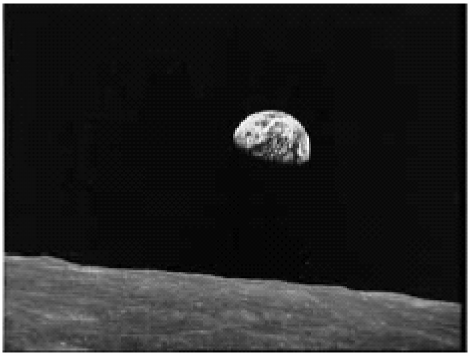

Figure 8.1, Lunar Exploration must be Global Enterprise[112]

8.1.2 Objectives of Lunar Exploration The science, economic and security objectives stated in the Broad Area Announcement for focusing a lunar exploration program have been examined in different forums and most recently again by the Presidential Commission on Space Exploration. An even higher priority for this phase of the program than these objectives is the goal of establishing the technology and experience base to enable continued and expanding human and robotic exploration of space. This is the spirit of the Presidential vision and is critical to achieving many other goals, primarily, building a capability to live, work, and eventually thrive in space. Some of the objectives (table 8.2) began to be addressed by the Apollo program, but many of them require a continuous and self-sustaining presence on the moon.

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[112] Huntress, Wes. et al., *The Next Steps in Exploring Deep Space*, International Academy of Astronautics Study, 2004, p. 93.

Table 8.2 Lunar Exploration Objectives

Area	Objectives
Programmatic	Understand the problems of long-term isolated habitation on a planetary surface Develop technology and techniques required for exploring and utilizing space Develop and prepare logistics infrastructure to support interplanetary missions
Scientific	Perform lunar geoscience Conduct solar and earth observation, and astronomy and astrophysics research Perform materials research, including the use of in situ local resources Perform medical research on low-gravity-induced physiology Conduct research too hazardous or dangerous for Earth (e.g., testing nuclear thermal rocket engines)
Economic	Develop applications of material engineering and medical technology Develop lunar extractive industry based on mining and the production of useful products (e.g., rocket propellant) Produce a return on investment: create new markets and economic growth
Security	Construct large earth-observation platforms Develop a cislunar transportation infrastructure Develop systems for protection from cataclysmic asteroid impact Establish a strong U.S. presence in cislunar space

8.1.3 Lunar Exploration Requirements A lunar program must be designed to address the objectives shown in Table 8.2. The objectives stated are challenging and will require a permanently-crewed lunar base with a sizable crew. For a lunar base, a crew of eight is considered a minimum and a larger crew is required to accomplish the full set of objectives outlined in the President's vision. Lunar base designs traditionally partition a lunar expedition into three stages – the tin-can/shrink-wrapped stage, which typically supports up to 10 people; the inflatable/assembly-required stage, which can support up to 100 people; and, subsequent permanent (underground) habitats, which are greatly expandable. These larger installation options have been challenging to implement. For that reason, traditional designs include the tin-can base as a stand-alone goal, and require that the smaller option satisfy some representational fraction of all program objectives.

As shown below, a higher capacity transportation system allows for the design of a program to meet the objectives instead of trimming the objectives to fit a limited capability. The space elevator concept is working to meet the full set of objectives through the first two phases of the program: the initial outpost stage and a laboratory stage. A successful program at this level has a higher return; the ability to captivate the public's interest; and, is more suitable to the primary long-term goal – safe, sustained human exploration of the solar system. An operational space elevator could easily, and inexpensively, supply these levels of payload masses to the needed locations beyond LEO.

An overview of the first two stages of a human lunar exploration program based upon work by Koelle (2004 NASA BAA) and Eckart, 1999:

Table 8.3 Human Lunar Exploration Phase 1: 3 years

Attribute	Comments
Crew size	8
Delivered mass at start of habitation	500 tons
Yearly supply rate per crew member	4 tons
Crew rotation time	0.5 years: 200% of crew rotates every year
Activities	Build and expand base, conduct physiology studies

Table 8.4 Human Lunar Exploration Phase 2: 15 years

Attribute	Comments
Initial crew size	8
Facility mass at start of this phase	1000 tons
Ave. crew size during 15 years	30
Accumulated mass at 15 years	30000 tons
Yearly supply rate per crew member	4 tons
Crew rotation time	2 years: 50% of crew rotates every year

Equipment lifetime attrition	20 years: 5% of equipment has to be re-sent every year
Contingency mass time	40 years: 2.5% of contingency mass has to be re-sent every year
Mass delivered per year for scientific or commercial activities	100 tons
Activities	Expand base facilities and capabilities Conduct human physiology studies Achieve long-distance surface transportation ability Conduct lunar geology, astronomy, and earth observations Develop technology for permanent habitation Develop commercial and security programs Prepare for interplanetary expeditions

It is important to realize that program size and duration determines program cost. This sensitivity is demonstrated by presenting the key data on four differently-sized programs (see table 8.5). Moreover, any long-term program will undergo changes with respect to goals and/or speed because it is subjected to political and economic priorities. Financial allocations will also be made on the basis of perceived success or failure. Consequently, a reference model must also provide information on the effect of such changes in the scope of the program to adjust the program in either direction. The characteristics of selected near-term and long-term program variations are compared in the next table.

Table 8.5: Comparison Lunar Development Scenarios

Type of lunar installation	**Outpost**	**Laboratory**	**Base**	**Settlement**
Operational life cycle (development+ operational. Years):	10+10	10+30	10+50	10+50
Life cycle average crew:	14	69	274	561

Maximum number of lunar crew:	19	85	463	1000
Accum. Lunar labor years	141	2,058	13,700	28,065
Accum. Labor years available for R&D	54	741	4,915	10,650
Accum. mass of facilities (1,000 Mg)	0.47	1.52	4.2	8.0
Accum. mass of imports (1,000 Mg)	0.98	6.7	27.8	55
Accum. mass of lunar products (1,000 Mg)	0.3	42	363	1,477
Accum. Passenger roundtrips	420	2,480	9,080	16,280
Accum. Acquisition cost ($B)	26	34	39	46
Accum. Recurrent cost Lunar Base ($B)	6	23	60	120

[note: Mg is megagrams or 1000 kilograms; accum = accumulated]

These lunar models were produced using LUBSIM by Koelle for the BAA proposal. Additional redundant systems are not included in these models but similar facilities are included in the "Base" and "Settlement" scenarios. The model has a complete set of inputs for base components that can be adjusted for different scenarios. The scenario presented here is comprissed of a generic set of possibilities.

8.2 Proposed Lunar Exploration Design Concept

This lunar exploration concept is based upon an innovative transport system (*The Space Elevator*, Edwards and Westling, 2003) and well-studied modular or prefab lunar base structure designs, modified to take advantage of a space elevator's capabilities. Figure 8.2 shows the infrastructure for Lunar exploration exploiting the strengths of a space elevator. This unique program has a number of benefits.

Figure 8.2, Earth Moon[113]

A space elevator is used for delivery of cargo from Earth to L1, the lunar surface or lunar parking orbit, and delivery of a crewed Crew Exploration Vehicle (CEV) from geosynchronous orbit (GEO) to L1, lunar orbit or the lunar surface. A medium-lift launcher delivers a crewed capsule (T-CEV) to Low-Earth Orbit (LEO) or GEO, where it is docked with a reusable space-resident Earth-moon propulsion module (IS-CEV). A view from around the Earth could look similar to Figure 8.1 for those on the way to the Moon.

Initial habitation modules and all supporting hardware (including return CEVs and contingency hardware) are placed in orbit (LEO, GEO, L1 or lunar orbit) or on the lunar surface before the first crew is launched. The first crew stabilizes the habitation environment, and immediately begins work on larger, modular, prefab habitats.

By providing supplies and safe havens at various locations (LEO, GEO, L1, lunar orbit, lunar surface) and constructing CEVs that can reach multiple destinations, the launch capacity of the elevator is used to gain operational flexibility and safety. These depots can be modular and low-tech; thus, establishing them will be inexpensive compared to permanently crewed habitats. This translates into inefficient use of propellant and hardware; but, with low launch costs and high capacity based upon a space elevator, NASA could seriously consider achieving a sustainable and expandable space exploration program.

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[113] Huntress, Wes, etal. *The Next Steps in Exploring Deep Space,* International Academy of Astronautics Study, 2004, p. 33.

Where possible, in-situ resources will be exploited to minimize the mass that must be transported to the lunar surface. Classic examples are using lunar regolith for shielding and extracting oxygen from various lunar oxides. In early stages, the use of lunar propellant to reduce the cost of transportation between the lunar surface and orbit may be effective; but, this will need to be traded against the reduced cost of bringing propellant from Earth. However, to make the most use of lunar resources, photovoltaic cell production from lunar materials must be considered.

8.2.1 Lunar Base Lunar base designs will be derived from the large body of existing work, optimized to take advantage of a space elevator's capabilities. The constraint on delivery of mass to the lunar surface is largely removed by implementing a space elevator. As the mass constraint is loosened, less design effort is required and more easily designed or overbuilt systems become more cost effective. In addition, there is lower risk and higher safety because of the inherent design of an elevator to the stars. An elevator also allows consideration of launching large or fragile structures intact.

With this new set of working parameters the system-of-systems analysis will find viable options in large-volume rigid structures for habitats (spheres, boxes, or cylinders over 10 meters in dimension), or mass-produced modular units that may be more massive but can be made easily, inexpensively, and safely with large risk margins. Examples of this can be found in terrestrial commercial applications (liquid storage tanks). In life-support systems we find that large-volume biological life support system enclosures may be viable as are the closed cycle life support systems that require large initial mass but provide better long-term affordability. The same type of trade will be examined for power systems (large scale photovoltaic arrays for a power-rich outpost), multiple surface mobility systems, and scientific facilities.

8.2.2 Transport System Description

- Earth-to-space transportation has always been a major stumbling block in cost and reliability to orbit. A space elevator would provide the capabilities required to meet Exploration Initiative objectives. The entire transportation system consists of two space elevators, Earth-to-space and in-space CEVs, and cargo modules.

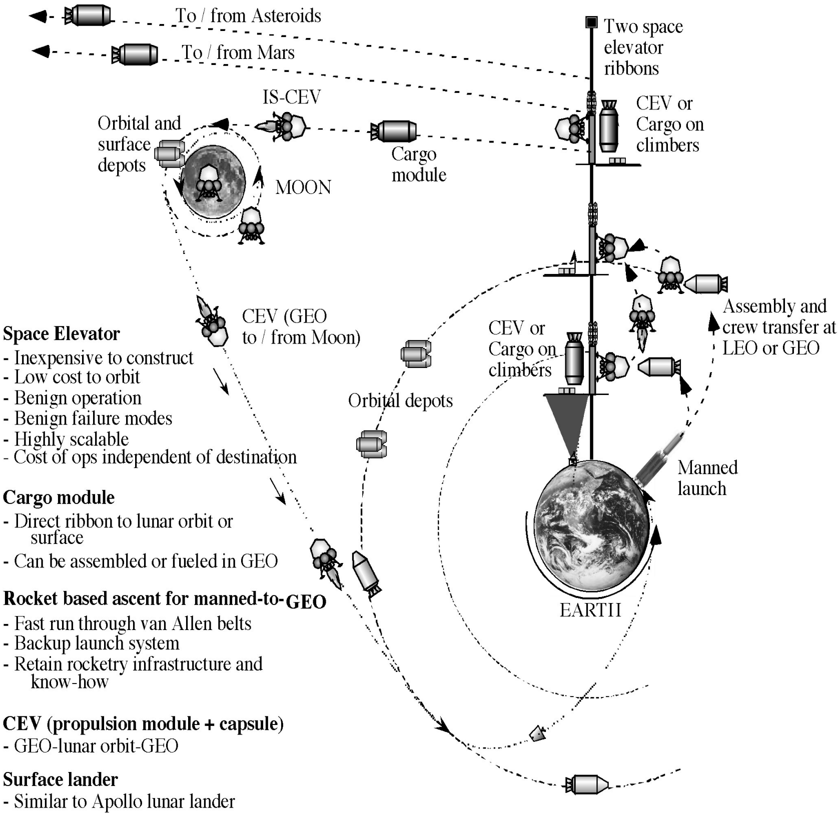

Figure 8.3, Overview of a Proposed Exploration Program[114]

Once again, the elimination of restrictions on mass will greatly enhance space exploration. A space elevator based transportation concept, structured around human transportation by rockets and all other space infrastructure mass by a space elevator, offers the following advantages:

- Low launch costs
- Relatively simple and inexpensive construction and operation
- Benign operation environment (no launch forces, no fairing to limit volume)
- Benign failure modes

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[114] Ewards, Bradley C., et.al., "Space Elevator-Based Program for Lunar Exploration," BAA 04-01 – Concept Exploration and Refinement, to NASA, July 16, 2004.

- Scalability
- Cost and operations are largely the same for a space elevator independent of destination

Excess launch capacity that can be utilized for other space programs or sold to lower total price

8.2.3 Utilizing the Space Elevator A baseline space elevator system considered in this book consists of:

- Two elevators
- 13-ton payload capability (expandable to at least 130 tons)
- 1500 tons per year / elevator from Earth to destination
- Operating cost of $1B / year for two elevators
- Construction costs of $15B for the first operational elevator by 2019
- Construction costs of $5B for second operational elevator 1 year later

<u>Cargo</u>: The space elevator is primarily used for cargo. Cargo will be transported up the elevator to beyond GEO altitude where it will be released on a translunar trajectory. Alternatively, cargo can be taken to GEO where it can be assembled or crewed. The complete payload is then taken, by climber, up the elevator for release into a translunar trajectory. Above GEO the elevator and standard climbers can handle payloads up to 150 tons or more due to the reduced forces.

<u>Crew</u>: In the current space elevator design, travel time from Earth-to-GEO on the space elevator is 8 days. Due to this excessive length of time for humans, the baseline crew transport is designed around conventional rockets. This will require human-rating a medium-lift rocket capable of carrying a transport CEV to LEO or GEO. From LEO, an in-space CEV delivered and fueled by the elevator can transport crew members to GEO. Once at GEO, crews will board in-space CEVs to be carried up the elevator to the trans-

lunar trajectory release point, where the elevator's velocity places them on course for a specified destination, with no propellant needed.

8.2.4 Earth Orbit Activities

Activities at LEO or GEO include:

- Crews transfer between the rocket-launched CEVs, if required, and in-space CEVs
- CEVs are refueled
- Large lunar/interplanetary cargos (e.g., Jupiter Icy Moon Orbiter) are assembled
- CEVs and other components delivered by the elevator are stored for emergency use
- Modules and other components delivered by the elevator are stored prior to assembly

In the long-term, a crewed station at geosynchronous altitude could be a station for originating exploration missions and conducting commercial endeavors such as solar power satellites, zero-g fabrication, and satellite repair.

8.2.5 Crew Exploration Vehicle

<u>Earth-to-Space Transportation CEV (T-CEV)</u>: If crews are transported up the elevator from Earth, the T-CEV will be required to have radiation shielding and living facilities for up to 8 days. An emergency aeroshell may be required pending a complete risk assessment of the elevator. If Earth-to-space transportation is to be by rocket, a rocket-carried T-CEV of a design similar to the Apollo capsule will be required. To use current rocket systems, after human-rating, then this T-CEV should have a mass of 5000 kg and be able to carry a crew of four. For comparison, the lunar command module had a mass of 5800 kg for a crew of three, provisions and hardware for the lunar mission. An aeroshell and braking engine will be attached at GEO on return if aerocapture is to be used instead of crew transport down the elevator. Based on the Apollo lunar command module we expect the cost of development of the T-CEV to be approximately $1B and replication to be $100M.

In-Space CEV (IS-CEV): The baseline IS-CEV in this concept is remotely similar to the Apollo lunar lander. The IS-CEV will be transported up the elevator on a climber either with a crew or the crew will board at LEO or GEO. If the crew boards at LEO the IS-CEV will use elevator-delivered fuel to move to GEO. The IS-CEV will be fueled at GEO and taken by climber up the elevator to the translunar trajectory release point and deployed to its lunar destination No fuel is required for this event. The IS-CEV will be designed to carry a crew of four for four days and land on the lunar surface. Upon landing, the IS-CEV will be refueled for ascent to lunar orbit or lunar escape. The IS-CEV will have a dry mass of roughly 12,000 kg (~3 times the Apollo lander) with a liquid fuel capacity of 16,000 kg. This is sufficient fuel to conduct any of the propulsive events that may be required (max delta-V expected is ~4 km/s for lunar surface to lunar orbit, trans-Earth injection and entering geosynchronous orbit at Earth). An additional stage will be required if LEO is used as the initial staging point. The 12,000 kg dry mass will allow designs that don't require tight mass restrictions, improve reliability and minimize refurbishing requirements. Primary differences with the established Apollo designs are larger mass, larger crew, elimination of the launch forces currently experienced during Earth launch and a requirement to reuse and refuel. Extrapolating from the Apollo lander costs it is expected that the development of the IS-CEV will be $1.2B with replication costs of $160M per unit.

8.2.6 Cargo Module The cargo module is a reusable or recyclable direct landing system for cargo transportation from Earth to the moon. Its lifecycle is:

- Carried up the elevator to GEO or to a release point for leaving Earth's gravity well
- If at GEO, used or combined with other cargo for delivery elsewhere
- If released on trajectory, perform necessary maneuvers
- If the cargo is surface-bound, perform landing

After landing the module may be:

- Dismantled for storage units, habitat, etc.

- Refurbished for emergency escape module or lunar-to-orbit (lunar or GEO) delivery

The cargo module will be a variant of the IS-CEV and is expected to have very similar engineering but a lower cost, as it is not human-rated.

8.2.7 Lunar Parking Orbit As a low energy destination from the lunar surface or GEO, lunar orbit or L1 can be useful for several applications:

- Storage of emergency supplies for rapid delivery to the lunar surface
- Staging point for module assembly of large ships and stations
- Transfer point from minimal surface-to-orbit vehicles to larger lunar-to-Earth vehicles

8.3 Key Engineering and Programmatic Factors

8.3.1 Safety The safety aspects of this program are unlike any other to date. The fact that operations are to be long-duration, and continuous, means that mishaps will eventually happen. How mishaps are dealt with is critical. Key to recovering from unexpected situations is flexibility, and flexibility stems directly from capabilities. In many cases the requirement for mission flexibility will conflict with design simplicity or mass limits. An integrated all-in-one system may appear more robust in the short-term but fall short in the long-term by a more staged, modular, flexible system. The large mass capacity of an elevator will allow crewed components to be over-designed, and carry ample propellant surpluses, allowing for greater mission flexibility, recoverability, and ultimately, sustainability. Redundant fuel, supplies, habitats, rovers, parts and CEVs can be placed in geosynchronous orbit (100 metric tons: four T-CEVs, habitat and provisions for eight people for two months) and lunar orbits (200 metric tons: four T-CEVs, two IS-CEVs, habitat and provisions for 16 people for two months) and on the lunar surface (300 metric tons: five IS-CEVs, eight rovers, five outposts, supplies for 16 people for two months) to provide multiple back-ups for exploration endeavors.

8.3.2 Affordability For the proposed program the costs can be broken down into system and delivery costs. From Koelle's lunar model, the lunar outpost system cost is $32B over 20 years with the bulk of this accrued between 2010 and 2022 for an outpost with an average crew of 14. The larger laboratory model amounted to $57B over 40 years with an average crew of 69.

For delivery there is a $20B capital expense and $1B/year operating costs for two space elevators that will be able to lift 3000 tons per year from Earth and throw it directly to the moon. This capacity is more than sufficient for any of Koelle's four models. However, there is a possibility of a commercial component of the exploration program that would allow NASA to reduce its expenditures by using the excess launch capacity for revenue generation. The CEVs are expected to cost a total of $2.5B for development and production of eight IS-CEVs and $2B for development and production of eight T-CEVs. The cargo modules are expected to run $1B for eight.

The next diagram (Figure 8.3) shows the timeline of NASA's Lunar/Mars exploration with an estimate of space elevator cost profile. The essential conclusion with respect to costs is shown here.

Program expenditures for a space elevator infrastructure are estimated to be $68 B, primarily spent between 2005 and 2023.

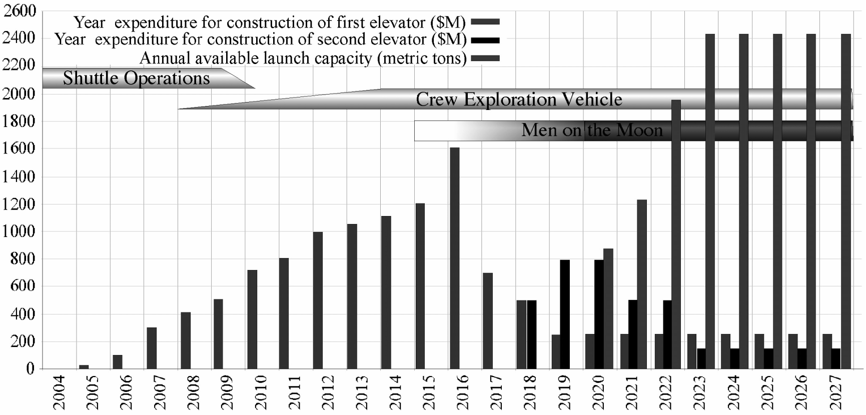

Figure 8.4, Space Elevator Funding Profile with NASA Exploration Plan[115]

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[115] Edwards, Bradley. "Current Status of ISR's Space Elevator Program" 3rd International Space Elevator Conference, Washington DC 2004.

The funding outlays for the outpost scenario can be scheduled such that the total, system and delivery, annual expenses will ramp up to a peak of $5B in the year 2020 and then taper down to less than $2B per year. As much as $2B per year may be recoverable through sale of the excess launch capacity (conducted by a private enterprise possibly on a lease program). In this schedule, by 2019 the first human will be safely on the moon. By 2022, a permanent human outpost on the lunar surface will be established and the next stage, a laboratory level lunar program, can be initiated. Modification to the lunar base due to implementation of a space elevator will further reduce the base construction costs due to simplified engineering and improve safety margins by allowing for more redundancy and back-up systems.

8.3.3 Extensibility/Evolveability This scenario is adaptable to exploration of Mars and asteroids. Modular units with similar construction to the IS-CEVs can be produced and joined to form larger living units (~200m^3) for longer duration stays. These larger modules can be released onto a trajectory with the elevator to Mars and near-Earth asteroids. As an Earth space elevator is equatorial, a plane change engine may be required depending upon the launch window. Once at the destination an individual module (with propulsion system still intact) would separate from the larger modular system for traversing to and from the surface.

In the long-term this scenario opens up the rest of the solar system. Long tethers at the Moon, asteroids, and Mars have been examined and found to be simpler to construct than an Earth elevator. These elevators could be assembled in Earth orbit and thrown to the destination of application. An elevator on Mars would allow for high-capacity transport to and from the red planet. On an asteroid it would allow for mining and delivery of mined material to other locations. Asteroid tether elevators could also be used for trajectory change and velocity boosts to the outer planets.

In addition, development will be required for CEVs, lunar habitats and systems, orbital operations, and orbital fuel depots. An IS-CEV is needed for in-space transportation and landing on the moon but not for aerobraking. This IS-CEV will be an advanced version of the Apollo lunar lander. A larger crew will be accommodated and the IS-CEV will be a multiple use system. The lunar habitats and fuel depots will be similar to a conventional scenario; however, with the higher performance of a space elevator, the designs may be less constrained and more depots and back-ups will be possible.

A T-CEV could be similar to the Apollo Command Module, orbital space plane or Lunar Excursion Vehicle (NASA's *90-Day Study of the Exploration of the Moon and Mars*, 1989) which are at TRL level 6–9.

Utilizing two space elevators in the exploration program leads to the capacity to launch 3000 tons to the moon each year for a total operating cost of roughly $1B. This capacity will allow for expeditions of larger and more crews if desired and considerably more hardware and autonomous systems. All of the objectives can be achieved at a credible level for a lunar exploration program and extension to Mars and beyond.

8.4 A Workable Space Exploration Program

The assumption is that the constraints placed upon prior NASA exploration programs still exist: 1) it must be valuable or of interest to the public and 2) it must have a total cost of much less than $500 billion dollars. As the Apollo program failed to convert into a long-term, self-sustaining program, the realization becomes one that placing a couple people on the moon or even Mars for a few days a year is not sufficient. For a program of 20 years, the program must do much more than Apollo which was a 10-year program, 40 years ago. This may be a permanently manned base with valuable activities such as manufacturing or scientific studies. Due to safety considerations this means a base with a minimum crew of four; but, more likely eight. This is the lower limit of what can be done in a federally-funded exploration program. When thinking about a publicly-supported, federally-funded space exploration program of this extent it must have a support base larger than Apollo (40% of the adult population). Funding limits define the upper end of what can be considered for an exploration program.

To transport a crew of eight to the moon, rotate them out every six months and keep them supplied will require 150 tons to be delivered to the lunar surface per year or 8 heavy lift vehicles with the performance of at least a Saturn V. The habitat for this crew will require 500 tons and need about 20% replacement each year. This requires 25 additional heavy-lift vehicles initially and five more each year. If this lunar base is operated for 10 years, it would require 155 launches. A reasonable estimate is that these heavy-lift vehicles, reusable or expendable, would cost $1 B per launch since these vehicles are not yet developed and require higher performance than the $500 million per launch Space Shuttle. There will not be much cost savings due to multiple launches because there will be about 15 launches per year which is not dramatically more than seen by the current shuttle. The launch costs of this effort then appear to be around $155 B not including any development costs for the heavy lift vehicle. Funding is also required for development and construction of the hardware used on the lunar surface. Estimates for this hardware vary but can run from $50 to $100 B. The total cost then comes in at $20 to $25 B average per year for ten years – higher than the current $15 B NASA budget. It should be considered that the current NASA budget funds NASA centers and diverse programs and cannot be redirected to pay for launch vehicles or much of the exploration initiative without politically-nonviable lay-offs in the thousands. In reality, NASA has a few billion dollars each year that can effectively be directed at the exploration program. Including efforts to go to Mars or to send robotic missions, the cost will increase dramatically. Considering two robotic missions a year and placing humans on the Martian surface to stay we find a funding profile equal to or larger than what we found above for the lunar base. This will place the total cost of a rocket-based exploration program at approximately $500 B. This is not much of a surprise as a similar exploration program proposed in 1989 had similar funding requirements. With realistic political fluctuations and other demands on the federal budget that occur over any 20-year time span, it is likely that this program will be cut or marginalized in a similar fashion to the 1989 program. To define a successful program there must be a much more valuable concept that costs less.

Early Conclusions: An analysis of a space exploration program based upon utilization of a space elevator has been conducted and found to produce a higher return at a lower cost than conventional rocket based programs. The reduction in cost is from roughly $500 B dollars to approximately $100 B where a large fraction of the remaining cost is for space hardware, not launch costs. The hardware costs may also be reduced when engineering for the less violent launch system is considered. The proposed program appears to be safer, more affordable and lower risk than rocket-based programs though the risks and issues are different for the two methods. The space elevator program also provides a large surplus of launch capacity available for commercial development.

8.4.1 Risk Assessment Utilizing a space elevator as part of the exploration program eliminates some risks and introduces others. Looking at the major subsystems of a space elevator, the Technology Readiness Levels (TRLs) for the subsystem components and entire subsystems range from 2-3 up to 9.

Table 8.6, 1995 TRL Levels for the Space Elevator[116]

Subsystem	TRL	Commentary
Anchor	6-9	Platforms are in operation, ribbon attachment system may require optimization
Spacecraft	6-9	Components are in use in this system are larger than standard
Climber	5-9	All components are in use though some not in this environment
Ribbon	2-3	The material is advancing quickly. A factor of 10 improvement in strength is expected within the year and the material ready for use within two years. Four separate approaches are being pursued to achieved the strength needed.
Tracking	8-9	Tracking system exists at low resolution and designed for higher resolution
Power beaming	6-9	Optical system exists in several applications. Required 100kW+ solid-state disk laser in construction at Boeing
IS-CEV	7-9	System is based heavily on units that have already flown (Apollo through ISS)
T-CEV	7-9	System is based heavily on units that have already flown (Apollo through ISS)
Lunar base	5-7	Systems have been extensively studied and components of specific designs have been utilized on the ISS
Cargo Module	7-9	System is based heavily on units that have already flown (Apollo through ISS)

Note: TRL levels 1-3: basic technology development; 4-6: prototype laboratory testing; and 7-9: technologies implemented in their final configuration.

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[116] Mankins, J.C., "White Paper," Office of Space Access and Technology, NASA,1995

The space elevator-related development risk of greatest concern is the high-strength material. Carbon nanotube materials are maturing rapidly due to commercial interest and with a modest investment can be produced at the strengths required and implemented in a ribbon within two years. The remaining technologies are nearing maturity and will be ready for use in the near future. A completed development and construction schedule for a space elevator has two years for development and 10 years for construction (Figure 8.4). However, some contingency was added: 3 years for development and 12 years for construction.

Estimates show that development and construction can be completed in 10 years -- following two years of R&D and with an additional 3 years for delays allowed. The space elevator can be operational by **2019**.

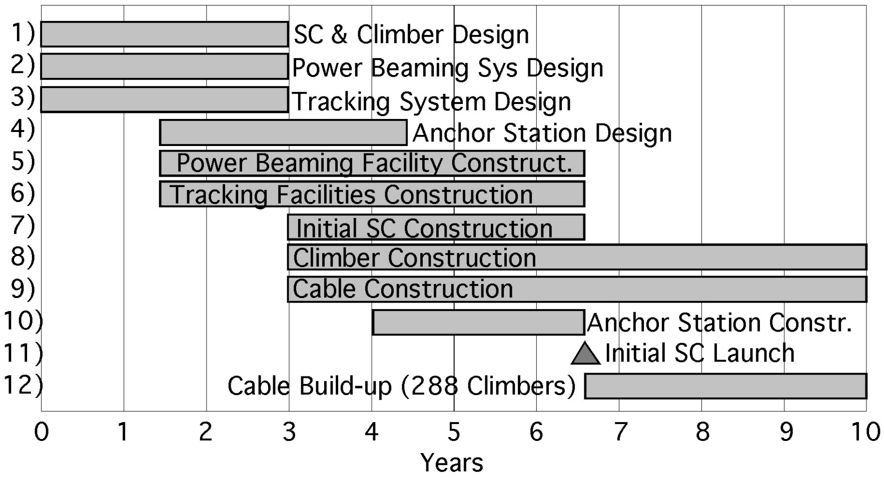

Figure 8.5: Top-level Construction Schedule (Edwards, 2003).

Conclusion

Space Elevator fits inside the funding profile
of NASA Space Exploration Initiative and will
provide tremendous leverage in tonnage
to the Moon and Mars.

To the Moon: A Visionary Architecture

The space elevator will enable humanity to reach beyond the Earth's gravitational well because it eliminates the restriction of mass to orbit with exorbitant costs. This capability will lead to the next step… back to the Moon. And then, humanity will continue to explore with the tremendous lever of a bridge to space. Maybe we can impact the following questions that are worthy of our endeavor.

CHAPTER IX – THE ROAD FORWARD

9.1 Realizable Dream

The world of the 21st century will be one of significant pressures driven principally by the increases in population and pressures on limited resources. This historic conflict has been observed in many forms: from the invasion of armies for conquering territory; to exploration opening up new lands; to industrial pollution; to rapid consumption of resources such as oil; and, finally, to conflicts based upon international perceptions of individual rights. The non-optimist would look at the situation and support the conclusions derived from studies such as "Limits of Growth" and "Reshaping the International Order" by the Club of Rome.[117] The optimist tends to believe that humanity can indeed improve the quality of life around the world through good intentions, international partnerships, global commerce, and of course, scientific discoveries and technological leaps.

9.1.1 Space Elevator Potential The phenomenal promise of a capability to provide access to space for $100 per kg could certainly help support the optimist's view. The following fictional scenario of the future is a dream of an optimist based upon elements of science, global needs, population, future projects and "break-out" technology products.

9.1.2 Global Scenario

Assumption: The space elevator is built resulting in $ 100/kg access to space.

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[117] Tinbergen, Jan, Anthony J. Dolman, and Jan van Ettiger. *Reshaping the International Order.* E.P. Dutton & Co., New York, 1976.

Leverage: The ability to get to space (specifically GEO altitude/orbit) for a low price enables the solar power satellite industry to mature and place multiple satellites in orbit. This capability leads to:

- Phenomenal new business opportunities for satellite and power industries
- Electricity available around the world at radically low prices
- Within industrial nations
    Hydrogen production plants at receive stations (with cheap, readily available, environmentally-friendly energy)
    Changes transportation industry through lower cost, minimum pollution
    Results in cleaner environment with lower price of goods and energy
- Within less industrial nations
    Leads to tremendous amounts of cheap energy at receive stations
    Leads to low cost hydrogen
    Leads to availability of affordable energy for all
    Leads to whole new businesses(many small, localized businesses)
    Electricity leads to personal connectivity (cell phones, computers)
    Results in millions of small successful economic zones

Around the world, the economy blossoms, pollution is lowered, and globalization of opportunity is realized.

9.1.3 Final Projection The potential global impact from a space elevator enabling space based solar power is a world with significantly less pollution and phenomenally more energy to people in all segments of the world community. The reduction in conflict over resources and the increase in communications and cooperation can only lead to a healthier global community.

9.2 The Road Forward – Recommended

The authors of this book would like to take the skills of a space systems architect and project the needed early steps toward realization of a space elevator. These steps are not all inclusive. They are an initial attempt to place the development of a space elevator on a path forward. They are:

- Identify needs and requirements
- Identify future markets
- Identify stakeholders and investors
- Create major effort to support carbon nano-tube development
- Initiate major architectural study to define a space elevator
- Initial trade studies on critical technical issues

The following sub-sections expand on these next steps to initiate the project.

9.2.1 Major Study to Identify Needs and Requirements The initial step should be a survey of potential customers and stakeholders to identify needs and requirements for a space elevator. One key item would be to refine the definition of a stakeholder and an investor for this mega-project. Some key elements that need definition for the Wright-Flyer Space Elevator are: total tonnage to orbit (by year); schedule of development; cost to orbit (by year); international participation; stakeholder, customer, investor and operational needs; orbital dynamics demands; strength to weight criteria; safety expectations; logistics support; and, communications needs. A study group should be established that would have a product, a systems requirements review, within 12 months.

9.2.2 Identification of Market The current Department of Commerce and Department of Transportation projections for payloads to orbit of approximately 100 launches per year is based upon current cost to orbit. This market projection is flawed by its assumption that access to space costs at least $20,000 / kg. An aggressive study must be initiated to assess current users of space, future traditional businesses restricted by the cost barrier, and future businesses enabled by the $100 / kg access to orbit cost. This market projection should be accomplished within a year and look at the global economy, not just the United States. This market projection should evaluate at least (not limited to) the traditional markets and Solar Power Satellites, Planetary Defense, Tourism, Science Community, Scientific Research, Resource Acquisition, Commercial Transportation, Communications Industry, and Exploration teams.

9.2.3 Identification of Stakeholders and Investors This top-level objective should be a high priority of the space elevator team. Identification of the entities who would most benefit from a successful space elevator is a must. These potential stakeholders should be approached with the proper estimates and desires, not a proposal. Initial discussions with at least the following entities would be beneficial:

- Energy Industry
- Private Investors
- Commercial venture capitalists
- US government: NASA, DoD, NOAA, DOC, DOT
- European Governments: UK, France, Germany, Italy
- Russian and Chinese Governments
- Major Industries: Boeing, Lockheed Martin, Northrop Grumman, Raytheon, Bechtel, EADS, ….
- International Organizations: UN-OOSA, EU, ESA
- Others as refined

9.2.4 Major Effort Support to Carbon Nano-tube Development The development of carbon nano-tubes is currently being stimulated by the fiber and composite industries as a method of getting a material with an extremely high strength-to-weight ratio. A parallel effort should be initiated to ensure that those researchers know the rewards of pushing toward a space elevator capability. A strength of 65 GPa is not "good enough." The researchers must keep pushing toward a space elevator capability of 130 GPa. To best ensure that research goals match space elevator needs, expectations must be explained and "bought into" by researchers. This expectation setting job should be the objective of this small team.

9.2.5 Major Study Defining Space Elevator Architecture This activity should be able to identify the approach for construction of a space elevator with a definition of the "to be" architecture. The approach the DoD has developed is a good model to ensure inclusion of major items and issues. The reason DoD went this route is that they were encountering major development projects that were systems of systems, or family of systems; but, definitely mega-projects. A study should be initiated to establish a Wright-Flyer architecture, loosely based upon the DoD architecture approach. One key strength of this approach is that most of the requirements for development are identified and most of the interfaces are specified prior to finalizing the actual design. A minimum set of these architectural views would benefit the total team. A suggested set for the first 18 months is provided in Table 9.1.

Table 9.1, Recommended Architectural Views

Number	View Name
AV-1	Overview and Summary Information
AV-2	Integrated Dictionary
OV-1	High-Level Operational Concept Graphic
OV-2	Operational Node Connectivity Description
SV-1	Systems Interface Description
SV-2	Systems Communications Description
SV-3	Systems-Systems Matrix
SV-4	Systems Functionality Description
TV-1	Technical Standards Profile
TV-2	Technical Standards Forecast

9.2.6 Identify and Institute Major Technical Studies Key trade studies to be conducted early in the Wright-Flyer development are:

- Ribbon Design (material, coatings, constant shape vs. variable)
- Location of Anchor (land vs. sea based)
- Anchor Infrastructure

- Standards for ribbon attachments
- Ribbon dynamics
- Climber architecture (types, velocity allowed, loads, driver motors)
- Command and Control (location-GPS, links-laser, operations center)
- Power options (laser, RF, solar, nuclear)
- Survival risk reduction
- Environmental issues
- Political support (international, local, country by country)

9.3 Schedule

The major studies should fit into the overall plan as shown in Table 9.2.

Table 9.2, Preliminary Schedule

Major Study	Initiated by	Report Due by
Needs and Requirements	Apr 06	Apr 07
Market Identification	Apr 06	Apr 07
Stakeholders and Investors	May 06	Dec 06
Nano-tube Development	Jun 06	May 07
Space Elevator Architecture	Jan 06	Feb 07
Institute Major Studies	Apr 06	July 06

9.4 Funding Profile

In addition to the near term schedule, the overall funding profile of the program must be understood and planned for. The normal space acquisition profile looks like Figure 9.1. This would give the team an understanding as to the spread of the funding after the mega-project has been initiated.

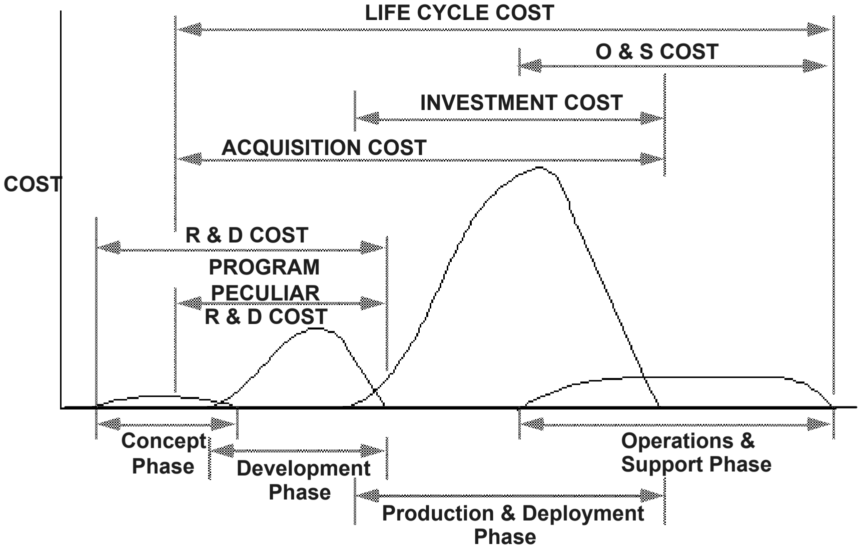

Figure 9.1, Life Cycle Cost Phases[118]

9.5 The Road Forward

This book provided a new look at a future Space Elevator project from a Systems Architecture perspective. The application of this discipline to a mega-project ensures a real engineering view from the top. The system of systems that is considered during this discussion is a "revolutionary way of getting from Earth into space, a ribbon with one end attached to Earth on a floating platform located at the equator and the other end in space beyond geosynchronous orbit. A space elevator will ferry satellites, spaceships, and pieces of space stations into space using electric lifts clamped to the ribbon, serving as

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[118] INCOSE Systems Engineering Handbook, available on the web. INCOSE. 2000.

a means for commerce, scientific advancement, and exploration."[119] Development of a space elevator is directed at the cost of access to space. The current and historic approach of launching satellites has become more refined, but is still described as "Building rockets… always on the edge of chaos."[120] This approach has two serious handicaps: only a small fraction of launch mass on the pad gets to orbit; and, the fuel and structures are all consumed. These handicaps lead to large inefficiencies and tremendous costs. One goal of the space elevator is to leverage an initial investment into access to space infrastructure and then take advantage of a routine transportation mode. The parallel to a bridge is evident, as the climber only consumes renewable energy. This leverage should lead to $100 (US dollar) per kilogram in the near future, and eventually, to $8 per kilogram after multiple space elevators are operating. The rocket infrastructure will change to being one around planets (and returning to Earth) while the "to orbit" infrastructure will be low cost, readily accessible, and open to all. George Whitesides stated… "Until you build an infrastructure, you are not serious."[121] The space elevator is designed to be ***THE*** space access infrastructure to orbit, the Moon, Mars and beyond.

To understand ***why*** a space elevator is needed, three components of the discussion were presented in the book.

- **The human spirit needs no restrictions:** Once the Apollo 8 picture of the Earthrise from the lunar orbit was broadcast, the world was sensitized to our limitations and the realization that we were on a fragile planet. We must soar beyond our boundaries and expand into the solar system. With an economical infrastructure, this can be accomplished.
- **The realization that chemical rockets can not get us beyond Low Earth Orbit:** The rocket equation requires that approximately 80% of the mass at the launch pad is fuel and 14% is structure, control equipment and other essential elements of a launch vehicle. This leaves roughly 6% for payload (mission satellite) that must be raised 300 km and

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[119] Web news release from Second International Space Elevator Conference – Sante Fe New Mexico – 12-15 September 2003.

[120] Robert Sackheim, "Panel Discussion," The Space Elevator 3rd Annual International Conference, 30 June 2004, Washington, D.C.

[121] Whitesides, George, "Panel Discussion," The Space Elevator 3rd Annual International Conference, 30 June 2004, Washington, D.C.

moved up to 7.9 km/sec in velocity. The tyranny of this rocket equation must be broken to enable commercial expansion into space.

- **The recognition that the "*Space Option*" will enable solutions to Earth's current limitations:** The space option is an alternative that is now open to humanity with access to space. Resources, expansion area and future hopes ride with the launch of each satellite and exploration activity. By lowering the price to orbit and ensuring an infrastructure that does not throw away 94 % of its mass every time it launches, that expansion can be real. Three important missions will be discussed that take advantage of the creation of an inexpensive and reliable access to space: solar power satellites, exploration of the solar system, and planetary protection.

The purpose of this book was to make the space elevator arena a little better understood, through the use of space systems architecture and space systems engineering. There is a large need in our space industry to understand this dynamic "to orbit" arena, especially as mega-project launch programs have all gone through financial problems. Not only will success rest on the engineering brilliance of the teams, regulatory breakthroughs in the international arena, and management of "mega-projects" in a timely manner; but, also in the customer enthusiasm toward lower cost to orbit and financial contracts for global service. This look at a Space Systems Architectural approach, as applied to the space elevator project, should assist the reader in the future with similar major endeavors.

A top-level introduction of a space elevator included looks at the project motivation, cost trades, regulatory issues, political issues, and technical considerations; including space elevator size, climber size, survival/risk reduction options, technical complexity, ribbon design, and elevator power needs. Application of the space systems engineering discipline allows an early look into the complexity of the system trade spaces and shows the current applications approach. Major issues were laid out in trade study style to provide easy access to key information backed by references, tables, equations and cost/benefit analyses. Critical understanding arises when key systems drivers are identified and laid out in such areas as ribbon design, ribbon manufacturing, space elevator deployment, market growth pattern, customer (client) needs, and basic systems engineering.

Indeed this book showed that the space elevator mega-project could successfully lead to movement off planet and belief in the following vision.

Space Elevator Vision

The space elevator gives us the road to limitless opportunities while opening up the solar system.

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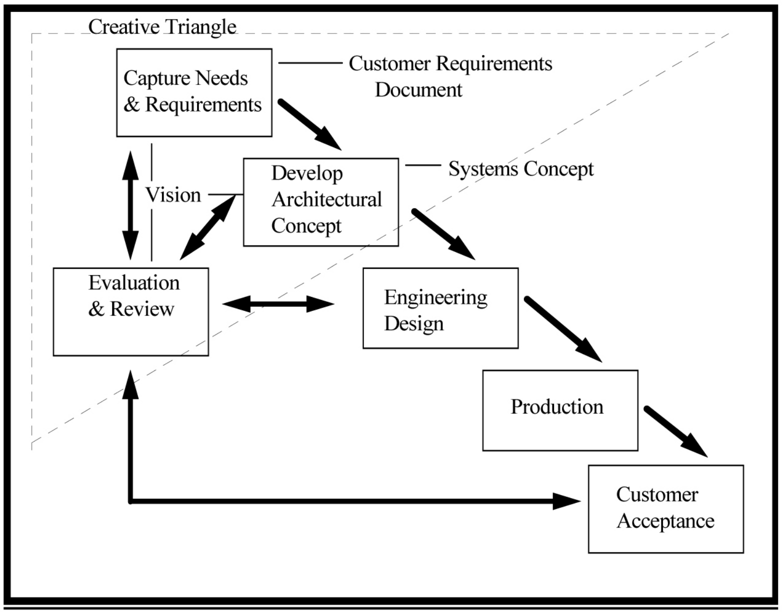
The authors present an initial look at an architecture for a space elevator. They expand upon the first space elevator book (2002 – Edwards and Westling) by utilizing a systems approach to development of a mega-project. A significant image (or snapshot) is given of an overall architecture of a mega-project with issues identified through an analysis of systems engineering trades. We hope this book will lead to an aggressive development program timed to match the growing excitement in the space arena today. This book project is focused around a:

Space Elevator Vision

A space elevator gives us a road to limitless opportunities while opening up the solar system.



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