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Safe Space Elevator – An Expectation to be Met Through a System Architecture Approach

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ABSTRACT

The expectation by the public of the safety of an elevator is "no worries." Everyone expects to arrive safely when riding an elevator… even a Space Elevator. As such, the survival of the Space Elevator must also have extremely high expectation levels. The Space Elevator is now a real engineering project and is indeed one of the latest projects being considered within NASA as a new technology path. It should also be considered across the international space infrastructure as a potential breakthrough. To enable this remarkable engineering feat, on a par with linking of Gibraltar to Morocco, an architectural approach must be used to ensure the safe operation of a Space Elevator. This paper discusses the various aspects of a Space Elevator's survival plan. This includes debris and meteorite mitigation. Some survival concepts are the flat ribbon design to defeat multiple small meteorites or debris hits; orbital debris reduction (its time has come); rules of flight for LEO, MEO, and GEO missions (nodal control); and, multiple base legs to anchor the Space Elevator as a counter for the threats of a LEO orbital environment. Appropriate methodology will be applied to the Space Elevator depending upon unique threat regions:

Low Earth Orbit: Excellent Tracking and Warning; De-0rbit of non-operational objects; Rules of the Road for new LEO spacecraft; and, Redundancy of Ribbons and Elevators below 2,500 kms (e.g. six ribbons in triangular arrangements to six terrestrial bases).

Medium Earth Orbit: Tracking and Warning; Capture of GPS like orbital debris; Rules of the Road; and, Ribbon Redundancy.

Geosynchronous Orbit: Tracking and Warning; Capture of old GEO sats (utilize the mass for Space Elevator counter weight); and, Ribbon Redundancy.

Super Geo Orbits: Tracking and Warning; and, Ribbon Redundancy

Key to the acceptance of any Space Elevator concept will be a systems approach across the total architecture for identifying and reducing risks. This paper will take a look at many approaches that will enhance its survivability. Segregation of the threat into altitude regions will lead to various priorities for many survival approaches. Indeed, a systems approach to the Space Elevator survival problem will change the issue from one that seems overwhelming to a recognizable risk issue that is well within current technologies and operational approaches. The expectation of a safe elevator ride is a must!

INTRODUCTION

Complex developmental projects have challenges that excite and demand a commitment spanning half a career or more. Simplicity in design is definitely a desirable outcome of early brainstorming for the development of a mega-project. The uniqueness of a Space Elevator is exciting for the designer and offers opportunities for imaginative and innovative thinkers. 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. 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.

ALTITUDE BREAKOUT

The rationale for segmenting the total Space Elevator into altitude regions is based upon simplicity and engineering scope. Solving local problems is always easier than global problems. This breakout enables the space systems architect and lead space systems engineer to compare and contrast across the total project, allowing optimization at the appropriate level. The following tables compare the regions by basic characteristics and the effects upon design. The approach this paper takes is one of 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. 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 survival aspects of the design will be presented along the altitude segregation regions, as shown in Table 1.

Table 1, Altitude Regions

Region	**From (kilometers)**	**To (kilometers)**
Super – Geo	37,000	104,000
Geo	36,000	37,000
SSO	2,500	36,000
LEO	Aero limit	2,500
Aero Lift	Sea Level	Aero limit

[GEO – geosynchronous; SSO – semi-synchronous; LEO – low Earth orbit]

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 paper will address the threats to a Space Elevator from meteorites, operational space objects, and space debris; propose a series of realistic mitigation techniques; and, apply 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 micro-meteorites
Space debris (expired spacecraft or fragments)
Operational Spacecraft
Space environment (x-rays, gamma rays, atomic oxygen, cold/hot)
Atmospheric environment (winds aloft, hurricanes, tornados, lightening, etc.)
Human environment (aircraft, boats, terrorists, etc.)

The threats logically separate into five regions and encompass all basic issues that must be evaluated. Figure 1 is from the International Academy of Astronautics draft report entitled, Position Paper on Space Debris Mitigation Guidelines for Spacecraft[1].

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

GEO Region: This region has the micrometeorite issue and human hardware intersection. The advantage is that the debris is mostly large and moving slowly when at, or close to, the "Geo Belt." The relative velocities are usually less than 100's of meters per second.

SSO 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 in circular orbits right above the lower limit of 2,500 km altitude and around the 12 hour orbit populated by navigation constellations (GPS with > 36 satellites; GLONAS with > 20 satellites; and the future Galileo with > 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 the Space Elevator and orbiting objects for the 12-hour region debris presents a serious threat for a Space Elevator.

LEO Region: This region has a major concern with space debris, a modest problem with operational satellites, and a smaller problem with micrometeorites, as shown in Figure 2. Most space debris has 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 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, etc.).

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

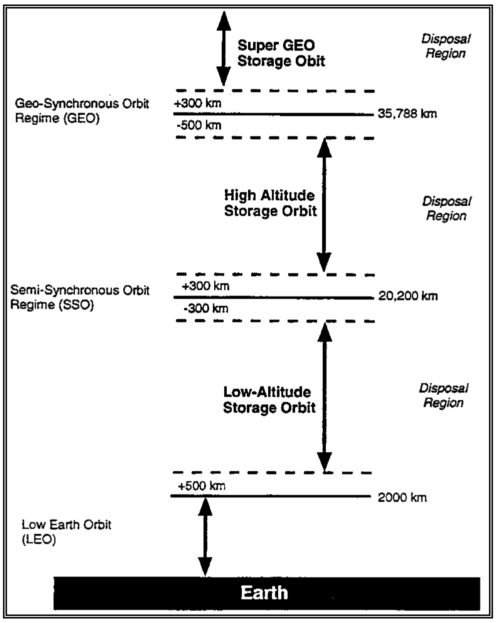

Figure 1, Region of Varying Threats[1]

SURVIVABILITY REMEDIAL 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.

Base Leg Redundancy – The LEO region (below 2,500 km altitude) presents a significant spectrum of threats such as debris, satellites, meteorites, winds, lightening and aircraft. This leads to the logical systems conclusion that multiple base legs should be installed for safety redundancy of a Space Elevator. (see parallel paper 3.8.2.09) The top altitude of the multiple legs (assuming 2,500 km), the optimum number of legs (assuming six), and the distance between the legs would be determined in a major systems study trading threats for survivable percentages. A key factor is that if a Space Elevator is 104,000 km long, five more base legs of 2,500 km each would be a modest additional complexity/cost and would provide tremendous redundancy.

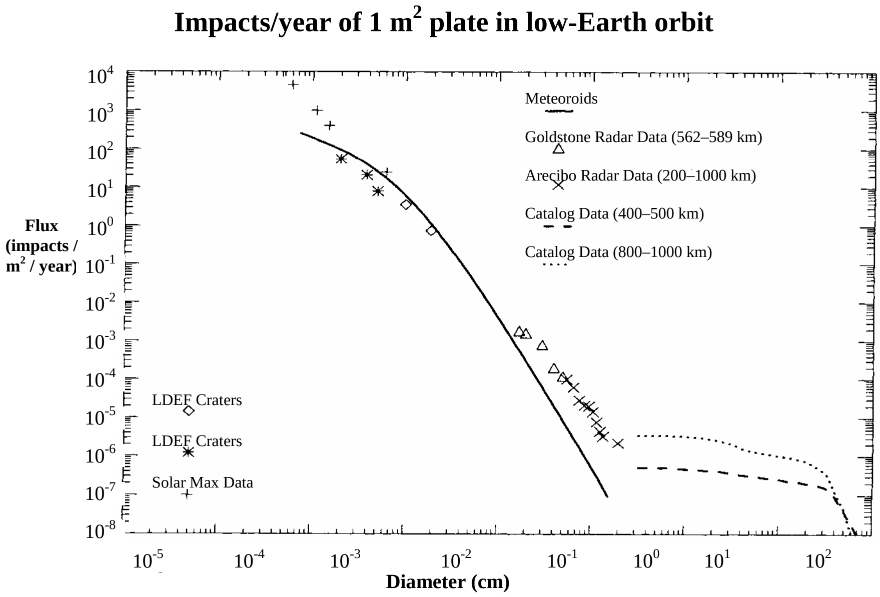

Figure 2, Impact Rates for Meteoroids and Orbital Debris[2]

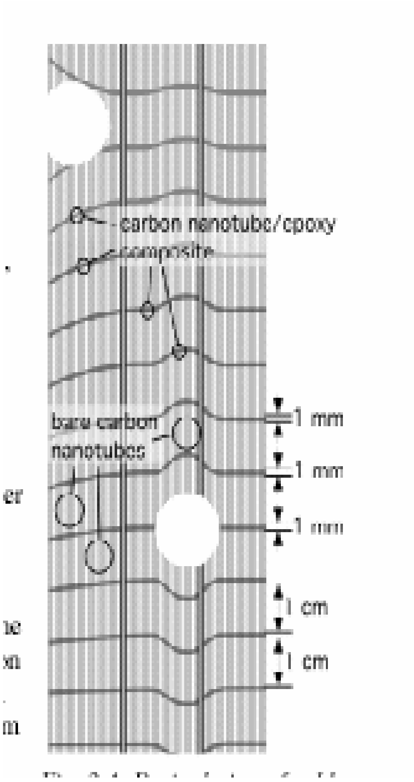

Figure 3, Ribbon Design[3]

[2] Space Mission Analysis and Design. Ed. III. Larson, Wiley & James Wertz. 2002. pg. 841

[3] Edwards, Bradley, "The Space Elevator," NASA report of NASA Institute for Advanced Concepts. Pg.16.

Ribbon Design – In this case, the ribbon design refers to the ability to survive multiple hits over its lifetime from the smallest meteorites and largest space debris. As the threat is for large numbers of small items of less than 1.0 cm, the survival of a Space Elevator must be from accepting the inevitable and allowing multiple hits per segment of ribbon over its lifetime. The principle source of these particles is meteorites and debris fragmentation, as shown in Figure 2, Impact Data for Meteoroids and space debris. 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 3.

Ribbon Redundancy – This technique is to be used for the inevitable, 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 (one person's satellite is another person's threat), and old rocket bodies. 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 used data from the debris community, an estimate could be made that a Space Elevator would be impacted by one of these objects (> 10 cm) every 1.2 years. 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). The design mitigation approach for this hazard consists of safety straps that would provide redundant capability for limited time (repair team required). Figure 4, Redundant Ribbon Design, shows the concept with each longitudinal segment of ribbon being backed up with two safety straps. The system trades for this approach includes how long each safety strap should be, maximum stress to survive when main ribbon is severed, methodology for maintaining separation of safety straps from ribbon, approach for repair, approach for notification of break, how to traverse ribbon while avoiding safety straps, and number of redundant safety straps.

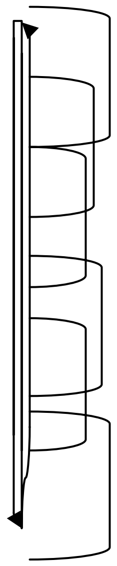

Figure 4, Ribbon Redundancy

Debris Reduction – Policy – The belief that we can continue to fly by the seat of our pants 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), a published[4] 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 wide 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, or so, 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

[4] Technical Report on Space Debris of the Scientific and Technical Subcommittee. Report of the UNCOPUOS. 1999.

LEO satellites create smaller pieces during or after operational use. The current thinking is that a policy could be implemented, and enforced, for "Zero Debris Creation."

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

a. grab and de-orbit
b. grab and maneuver as needed
c. grab and use 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. 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 its rotation in order to gain control for any action. To stop the rotation, angular momentum must be taken out 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 (10's of km) for rapid decay, whereas at MEO 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 (see section on repetitive/non-interfering 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 the counter-weight beyond GEO. 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 pound for inert spacecraft or rocket body de-orbit, or movement to a stabilized orbit. This would be roughly 9,000 pieces for $1 billion. Two papers have recently talked about the concept of attaching to space objects and moving them. ("The Electric Dynamic Delivery Experiment [EDDE]"[5] and "Study on Electrodynamic Tether System for Space Debris Removal"[6])

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 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. 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

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

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

crossing and avoid the vertical corridor of a Space Elevator. This is the current policy at GEO (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 affected and, perhaps, even enhanced.

Ribbon Motion – A Space Elevator can be moved from its stable position to avoid collisions. The risk of collision is real, as not all maneuvering can be mandated for debris; therefore, requires this capability. One benefit of a set of multiple legs is that changing the length ratios of the legs changes the location of the Space Elevator's vertical corridor. This motion could be modeled during the design phase to ensure that the dynamic stresses were included in the material selection and architecture. Of course, the changing of a base legs length ratio would move the lower portion of a Space Elevator more than the upper portions. This is desirable as most of the debris of concern is below 2,500 km.

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

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 2 shows various approaches and sets a prioritization for a systems solution against threats. The order for the solution set is different for each orbital region because of the resultant system trades between region vs. threat vs. mitigation approach.

Table 2 Systems Approach to Space Elevator Survival

	Aero Lift	**LEO**	**MEO**	**GEO**	**S-GEO**
Region (km)	< 40	< 2,500	>2,500 <35,288	>35,288 <36,088	>36,088
Threats	Planes, winds aloft, hurricanes, tornadoes, humans	Meteorites, Debris Density highest, Many inclinations and altitudes	Meteorites, Less dense debris	Meteorites, slow interactions satellite debris	Meteorites,
Methodology					
Ribbon Design	**4**	**5**	**2**	**2**	**1**
Ribbon Redundancy	**1**	**3**	**1**	**3**	**2**
Ribbon Motion	**5**	**1**	**6**		
Debris Elimination		**4**	**4**	**1**	
Satellite Knowledge		**2**	**3**	**4**	
Rules of the Road	**3**	**6**	**5**	**5**	**3**
Corridor Protection	**2**				

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 Ribbon Redundancy – As a backup for Ribbon Design, safety straps could be included in this region. The key to Super Geo is that periodic missions are sent from these high altitude locations and the continuity of a Space Elevator must be maintained.

Priority # 3 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).

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 ensure a design robust enough to survive.

Priority # 3 Ribbon Redundancy – A mandatory step when addressing the threat from large GEO satellites.

Priority # 4 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 # 5 Rules of the Road – Strengthen the GEO ITU rules to ensure no lost satellites or out of control inert bodies. Table 3 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 IADC report..

Table 3, GEO re-orbiting Practices[7]

	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**
Drift Orbit (acc. IADC)	7	7	4	2	2	**22**
Total	**17**	**21**	**12**	**11**	**14**	**75**

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

SSO

Priority # 1 Ribbon Redundancy – The key element in this region is dealing with large objects that could cut a meter wide ribbon with one pass. As such, the first priority is to have redundancy for a single large object threat.

Priority # 2 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 # 3 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 # 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 the navigation systems of today. As such, there will be multiple constellations at the "half way to GEO" location and large satellites must be controlled so they do not cross the equator at the precise location of the Space Elevator.

Priority # 6 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.

LEO

Priority # 1 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 item.

Priority # 2 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 # 3 Ribbon Redundancy – Below 2,500 km, the amount of space debris and meteorites drive the systems architect and systems engineer to a conclusion that it will be hit with a modest sized object within its 50 year lifetime. A backup series of tether strings could, therefore, be crucial to a Space Elevator in case of a cut. In addition, operational procedures must be in place to ensure recognition of cuts and rapid repair to continue mission materials flow.

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 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 # 6 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 Ribbon Redundancy – This high threat arena should have redundant ribbons. This would greatly assist security and diversify vulnerabilities to natural and man-made disasters.

Priority # 2 Corridor Protection – Rules of the Road for flights, boating, and driving will ensure that the corridor does not suffer from accidental collisions.

Priority #3 Rules of the Road – This is an extension of the priority #2, but applied to the international arena similar to maritime law or aeronautical treaties.

Priority #4 Ribbon Design – The ribbon must be designed for this unique transition from vacuum to sea level pressure. This transition will be dynamic and stressful for ribbon designers. However, the ribbon must be manufactured with the stated objective of "no failures" in whatever environment it is in.

Priority #5 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.

SYSTEMS' SURVIVAL SUMMARY

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. 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 be the wild west in space anymore. Rules must be initiated that would enable a Space Elevator vertical corridor to exist. Control of nodal passing must be orchestrated so that it can be a mature set of rules as a Space Elevator becomes a 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 terrestrial pollution.

Enhance a "Zero Debris" position: Currently the International Academy of Astronautics is publishing a position paper on space debris[8]. 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 project, 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 future systems (Preliminary Design Review after 2007) and, as such, would not impact their overall price. However, the positive impact on a Space Elevator and other future initiatives would be tremendous.

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

The final conclusion of a systems analysis for a Space Elevator that will survive debris, operational spacecraft, meteors and meteorites, and atmospheric threats is:

Start the Initiatives NOW !