New Space Elevator Mission Requirements Are Needed

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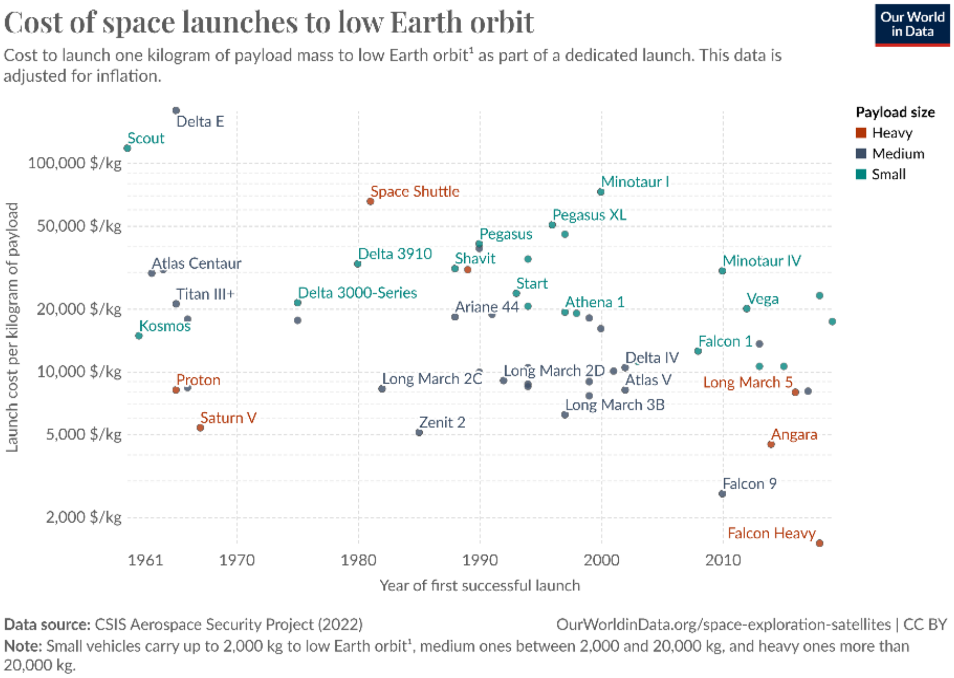
Abstract

The last twenty years have seen significant human advancement as a space-fairing society. SpaceX and Blue Horizon have advanced space flight with affordability as the key driver. SpaceX is pushing heavy-lift reusable rockets to impressive payloads in mass and available volume. Space elevators have made progress in creating designs that can achieve a mission requirement developed over twenty years ago. The open publications' cargo lift capability and elevator speed requirements have not changed for decades. More detailed designs and components have been analyzed, and the feasibility of a fully deployed system with various operation modes has been explored. However, SpaceX, Blue Horizon, the Artemis program, and other international efforts vying for space beyond LEO have expanded beyond the space elevators' original requirements and design solutions in an open forum. The question is whether the current requirements are still relevant or need to be updated. The original requirements were competitive with rocket solutions available over twenty years ago but have fallen behind various rocket solutions. Are these design solutions and technologies correct if the requirements and missions change? This paper will explore a recommended update to the criteria for space elevators to ensure they remain relevant to today's rocket competitors. A space elevator designed to meet these new requirements is shown to be the only viable means for humans to settle space in the thousands, tens of thousands, or millions.

Introduction

Space Elevator concepts have evolved from science fiction to serious technology development efforts over the last century. The change occurred with the invention of carbon nanotubes, which have a much higher tensile strength-to-density ratio than over tether materials previously evaluated. Serious efforts based on carbon nanotubes began in the late 1990s, and top-level space elevator requirements were created in an open environment to allow independent scientists, engineers, artists, dreamers, and businesses to develop concepts of systems, components, and technologies to meet the challenges of building, deploying, and operating space elevators that had meaningful payload capability compared to the alternative rocket technologies available in the late 1990s to reduce cost compared to rockets drastically, Figure 1 (CSIS Aerospace Security Project, 2022).



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Note: Small vehicles carry up to 2,000 kg to low Earth orbit¹, medium ones between 2,000 and 20,000 kg, and heavy ones more than 20,000 kg.

Figure 1 Launch Cost per kilogram has decreased with new rocket designs.

The International Space Elevator Consortium provides an open environment where space elevator enthusiasts and technical experts come together to mature a space elevator concept. ISEC has regularly organized and enabled the community to conduct studies and published reports, adding more detailed analyses and design solutions based on the 1990 initial system capability requirements. Rocket technology, launch operations, and business models have changed to increase overall rocket lift and volume capability while reducing costs based on the cost/kg per unit rocket launch, Figure 1. Several billionaires and other space enthusiasts have taken the lead in innovating space launch capability to create large-scale space settlements and a space economy that could be integrated with the Earth's economy. Lift capacity needs for large-scale space settlements and a functioning space economy are far beyond what has been launched for Earth's space launch efforts.

Current rocket capabilities are far beyond the rockets of the 1990s. This raises the question as to whether the space elevator requirements, which have been the cornerstone of all the ISEC open technology, system, and business case efforts for the last several decades, are still relevant (Swan et al., 2013) (Swan et al., 2019) (Phister et al., 2024). In addition, the invention and limited manufacturing capability of a newer carbon-based high tensile strength low-density ratio material, graphene, has expanded the design solution set beyond what carbon nanotubes are capable of for meeting higher capabilities for future settlements and space economy missions.

A top-down system requirements assessment was conducted to evaluate whether the previous requirements were adequate for developing and deploying an economically viable space elevator. Recommendations for new system-level requirements are provided for the space elevator community and ISEC to not only be competitive with rocket capability but also provide capability beyond the limitations of current rocket technologies to provide a mission completion timeframe that will be attractive to space settlement and space economy. In addition, the economics of various space elevator concepts to provide transportation services to complete various missions are discussed. The following paper summarizes this requirements assessment.

Mission Level Assessment

A basis of comparison since the beginning of the space program has been the lift capacity of a single rocket to carry a particular payload to a specific destination, Figure 2. The mission was

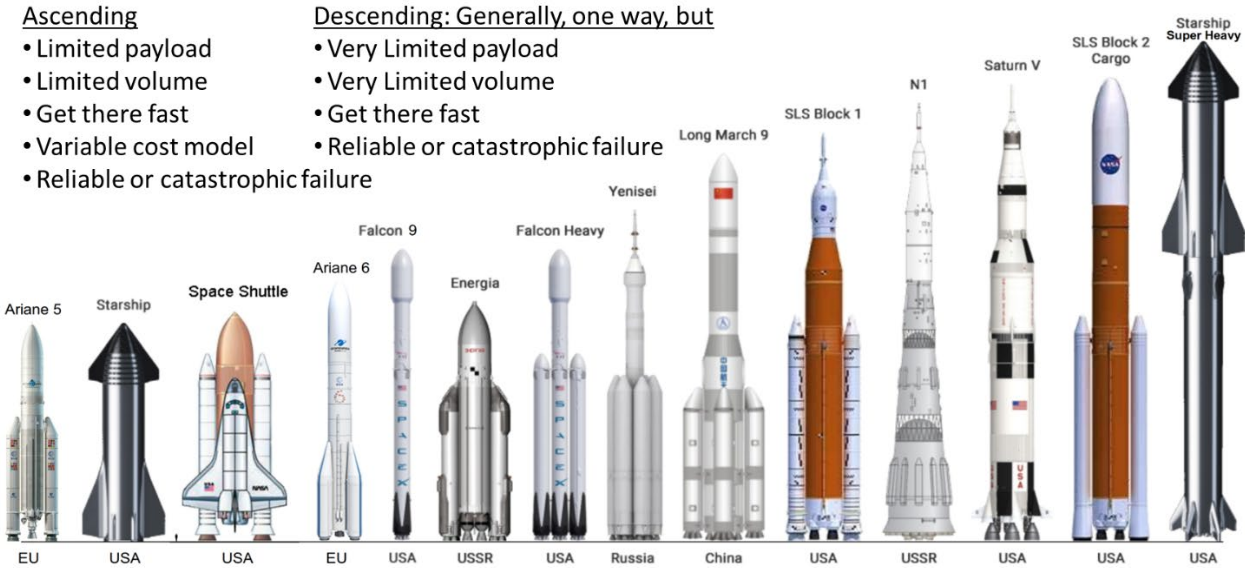


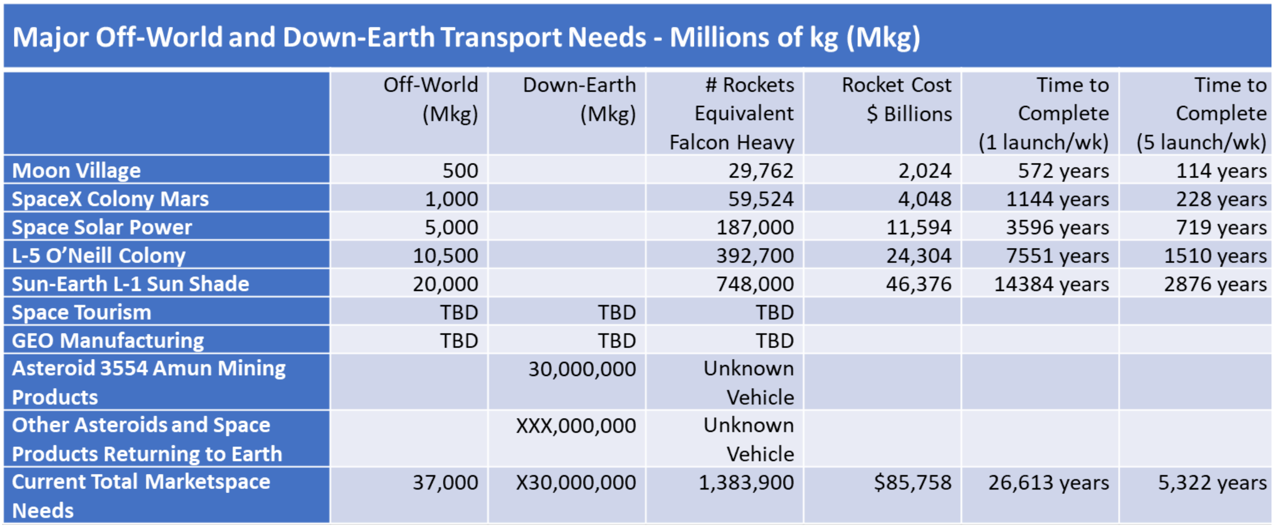
Figure 2 14 Largest Heavy Lift Rockets have a Very Low Payload Fraction of 1-3%

based on a single launch or built on a minimal number of launches. Settlement of space by hundreds, thousands, or millions of people will require far more launches than the total number accomplished by all the world's space programs. The basis of comparison must change to provide the overall performance and cost for the total mission. Previously, payload to a specific orbit or destination such as the moon, Mars, or other locations in the solar systems was the measure of merit. The mission was one flight and did not address the space settlement and space economy scenarios, which would take thousands and tens of thousands of flights.

The 14 largest heavy-lift rockets use chemical reactions to produce high-temperature gas that expands through a nozzle to produce thrust. The various chemicals are expended over the launch cycle, reducing the overall vehicle's weight, and fewer chemicals are needed to continue the launch of various "stages" that are ejected from the vehicle. Depending on the destination of Low Earth Orbit, Geosynchronous Orbit, Trans Lunar Injection, Mars Transfer orbit, or other flight profile, the payload is limited by the chemical energy available in a fixed volume. The payload is generally 1-3% of the overall mass of the rocket fully fueled.

Space settlement and space economy missions require many rockets launched to transport mass to a destination. Five essential missions have been used for decades, and several have recently been updated to reflect new concepts of space settlement and economy. Figure 3 provides the various missions for space settlement and economy. The first five on the list are the decades-old missions with updated mass projections. These five assume that all mass is leaving Earth and not returning. The other missions, from space tourism to space manufacturing and space mining, assume that there is considerable mass to bring back to Earth's surface. Manufacturing and asteroid production mass projections are far beyond what reentry vehicles can reasonably manage.

As a basis of comparison, the Falcon 9 Heavy is used to determine the number of launches required and the overall cost of transportation to complete the mission, Figure 3. Although there are rockets with higher payload capacity, the Falcon 9 Heavy has the lowest launch cost per kilogram, Figure 1. Once SpaceX Starship is matured with reliable performance and the cost per launch is verifiable, this assessment will be updated to determine if rockets appear more attractive. The Falcon 9 Heavy transportation solution will require tens of thousands to hundreds of thousands of launches to complete the missions. It will also require trillions of dollars in transportation costs alone, not counting the cost of the cargo or personnel it is



Major Off-World and Down-Earth Transport Needs - Millions of kg (Mkg)

	Off-World (Mkg)	Down-Earth (Mkg)	# Rockets Equivalent Falcon Heavy	Rocket Cost $ Billions	Time to Complete (1 launch/wk)	Time to Complete (5 launch/wk)
Moon Village	500		29,762	2,024	572 years	114 years
SpaceX Colony Mars	1,000		59,524	4,048	1144 years	228 years
Space Solar Power	5,000		187,000	11,594	3596 years	719 years
L-5 O'Neill Colony	10,500		392,700	24,304	7551 years	1510 years
Sun-Earth L-1 Sun Shade	20,000		748,000	46,376	14384 years	2876 years
Space Tourism	TBD	TBD	TBD			
GEO Manufacturing	TBD	TBD	TBD			
Asteroid 3554 Amun Mining Products		30,000,000	Unknown Vehicle			
Other Asteroids and Space Products Returning to Earth		XXX,000,000	Unknown Vehicle			
Current Total Marketspace Needs	37,000	X30,000,000	1,383,900	$85,758	26,613 years	5,322 years

Figure 3 Missions for Space Settlement and Space Economy Requires Billions of Kilograms Transport from Earth's Surface to GEO or Beyond, Which Requires Tens of Thousands of Rockets, Trillions of Dollars, and Hundreds of Years

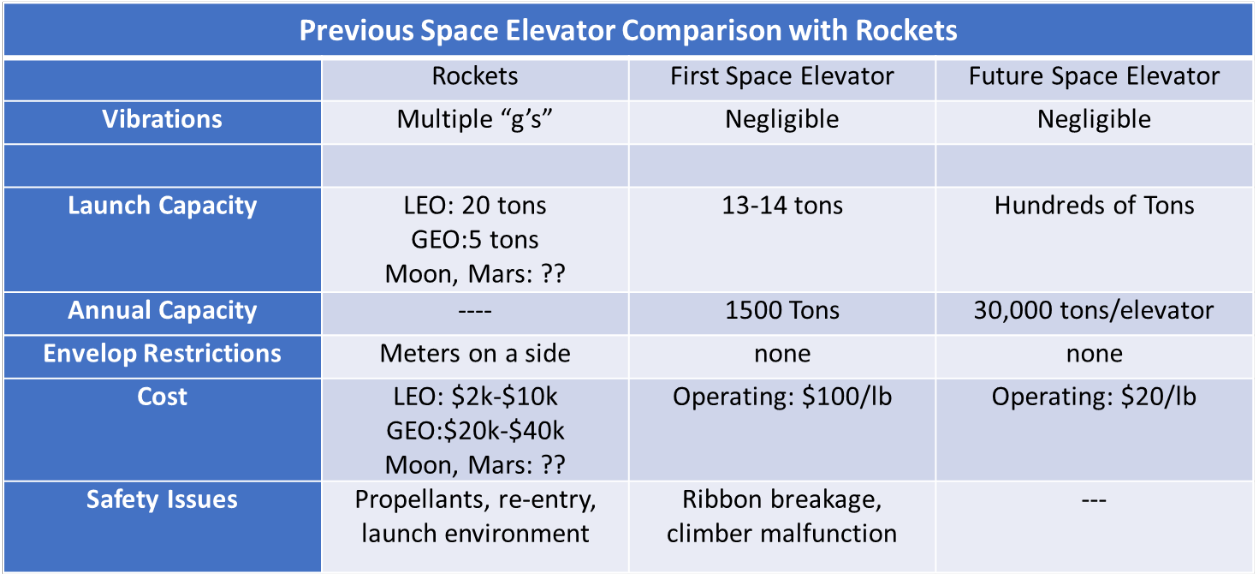
transporting. The most concerning performance metric is the time it will take to complete the missions.

Assuming a launch can occur once or five times a week, every week, it would take hundreds or thousands of years to complete the missions. Launches per week every week are possible for Moon Village, Space Solar Power, and an Earth-based LaGrange space station such as the L-5 location. However, a Mars-based mission or other considerable distance destinations will be based on a launch window to ensure minimal transit time and energy consumption. On average, the traditional Mars Transfer Orbit's window is approximately two months every two years. This would mean that the number of launches for the Mars mission would have to be increased twelve times, or the time required with the number of launches identified would increase by twelve times that specified. These numbers may change once SpaceX Starship Heavy is matured. However, hundreds and thousands of years based on rocket capability appears to be a non-starter from a mission perspective.

Current Space Elevator Assessment

A deployed space elevator must meet specific criteria for customers to view it as a transportation solution for space access. Mission, payload, cost, safety, volume, launch windows, launch locations, destinations, manned or cargo only, length of service, and disposal are some of the primary considerations for selecting a transportation system into space, Figure 4. Rockets were developed in payload classes from small lift to heavy lift but are limited due to the number of expendables required to lift and insert a payload into orbit or escape Earth's orbit for another destination in the solar system or beyond. Rockets balance the needed payload into space versus the rocket structure and fuel required to accomplish the mission. The payload to total rocket mass is 1-3%, depending on the mission and destination. SpaceX has attempted to reduce the disposable nature of a significant rocket section by safely landing it back to Earth, refurbishing it, and reusing it for future missions. This philosophy has dramatically reduced the cost of launching mass into space over other rocket solutions.

Space elevators are a system with various subsystems. Whereas a rocket is a stand-alone system, a Space elevator consists of a tether, a ground station, a power source, a climbing vehicle, a propulsion system, an end-of-tether mass, a variety of safety equipment, and near tether facilities, which could include manufacturing, hotel, training, assembly, or science-based platforms. The variability in



Previous Space Elevator Comparison with Rockets

	Rockets	First Space Elevator	Future Space Elevator
Vibrations	Multiple "g's"	Negligible	Negligible
Launch Capacity	LEO: 20 tons GEO:5 tons Moon, Mars: ??	13-14 tons	Hundreds of Tons
Annual Capacity	----	1500 Tons	30,000 tons/elevator
Envelop Restrictions	Meters on a side	none	none
Cost	LEO: $2k-$10k GEO:$20k-$40k Moon, Mars: ??	Operating: $100/lb	Operating: $20/lb
Safety Issues	Propellants, re-entry, launch environment	Ribbon breakage, climber malfunction	---

Figure 4 ISEC's Comparison to Rocket Launch Capability has not Changed Over a Decade.

solutions for a space elevator does not drive any one solution set as with a rocket. The physics of a rocket is set, and most rockets look and perform similarly. ISEC studies have developed an open-source climbing vehicle with several power sources and propulsion techniques. ISEC studies have also explored various tether configurations that add flexibility to operating a multi-climbing vehicle mission. The payload to vehicle total weight is 30-50% compared to a rocket, which is 1-3%. ISEC's comparison to rockets, Figure 4, has changed little over the last several decades and is based on a detailed study by Bradley Edwards (Edwards & Westling, 2002) published in 2002 when compared to more recent ISEC studies (Swan et al., 2013) (Swan et al., 2019) (Phister et al., 2024; Swan et al., 2019). Comparing the capability specified with the mission needs, the first space elevator will still take hundreds of years to complete the missions. The future space elevator with no credible solution will still take decades to complete missions.

The question is, what will the future space elevator requirements be based on the need for future missions? This will determine the success/failure and plausibility of human settlement in space and a space economy beyond just satellites.

Space Elevator New Requirements Generation

Our previous discussion has shown that rockets are not a viable solution to the desired future space missions, and currently developed space elevator concepts cannot meet the need either. We found that the rockets and current space elevators must be improved in several performance parameters: payload, cycle time, and mission completion timeframe. We have also identified other parameters of interest: cost, safety, volume, launch windows, launch locations, destinations, manned or cargo only, length of service, and disposal. These parameters will eventually need to be assessed to determine the total overall life cycle cost for completing a mission or all the missions identified. Focusing on rockets and elevators as transportation for cargo and people, the primary comparison parameters are payload mass, payload volume, cycle time per tether transition, and overall mission completion timeframe. It is paramount that space elevators be superior to rockets in these categories to ensure that space elevators are competitive and exceed the capability of rockets in GEO or beyond GEO missions.

Payload Mass - Starting with payload mass, one must assess a basis for comparison. Rocket manufacturers will quote a payload capacity that initially may sound impressive, but the capacity changes depending on the destination due to limits in energy availability. For example, transporting multiple small microsatellites into a low earth orbit can be one mission. Putting a 10,000-kilogram satellite into geosynchronous orbit can be another. Sending 50,000 kilograms to the moon can be another, Figure 5. These all required different rocket solutions based upon the payload, the volumes and the destination, the fuel required, and the orbital trajectory required to reach those destinations. If rockets are used as a transportation solution, the same rocket will have different payload capabilities depending on the destination.

The fourteen largest heavy-lift rocket systems employed over the last several decades, Figure 5, have different payload capabilities depending on the destination. By comparison of a Low Earth Orbit (LEO) payload to a Geostationary Transfer Orbit (GTO), Trans Lunar Injection (TLI), or a Mars Transfer Orbit (MTO), the payload rating at GTO will be 29 to 53% that of a GEO. TLI payload rating is 24 to 44% of LEO. GTO is 17 to 31% of the payload capacity of LEO for those rockets capable of accomplishing that mission.

The rocket solution is limited due to the mass fraction of payload to total vehicle weight and the knockdown factor required based on the differences between LEO and other destinations. Space elevators can have much higher mass fractions of payload to total vehicle weight depending on the design solutions pursued. Mass fractions can be as high as 70% under

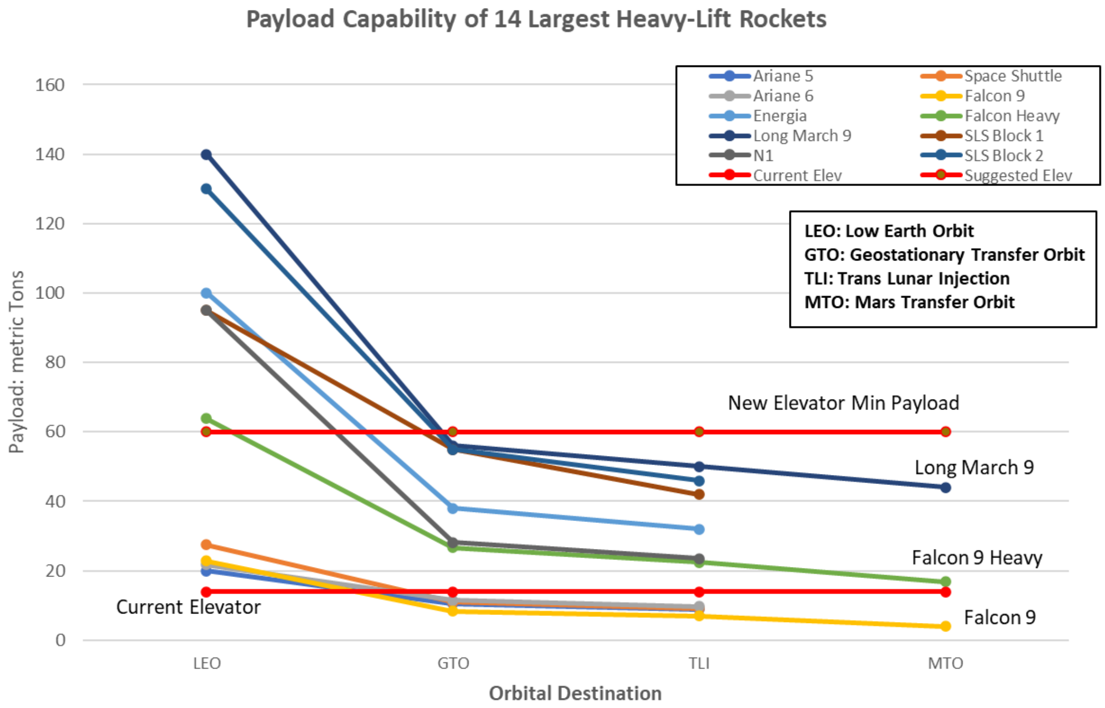


Figure 5 Payload Capacity of Rocket Versus Space Elevator Highlights Current Space Elevator Requirements Need to be Increased.

certain circumstances, which is far superior to the 1-3% for rocket solutions. This assumes that the space elevator vehicle does not use expendables as part of its propulsion system and that energy is provided off-vehicle. This design concept is the opposite of a rocket solution, which requires all energy within the vehicle.

Space elevators that do not use expendables have constant payload capacity no matter the destination. However, the current ISEC space elevator design payload of 14 metric tons is below that of various rocket solutions. If SpaceX Starship Heavy reaches its desired goal of 250 MT to LEO, then a Mars Transfer Orbit payload could be in the 80-85 MT based on the performance of other rocket systems.
It is suggested that, as a minimum, the ISEC space elevator should increase its payload capacity to 60 MT to be competitive with the current rocket solutions. It is further suggested that that goal be raised to 100 MT to ensure it will exceed any future SpaceX Starship Heavy capability. These preliminary payload requirements are to provide superior payload capacity over rockets for GEO and beyond missions. An alternative payload assessment

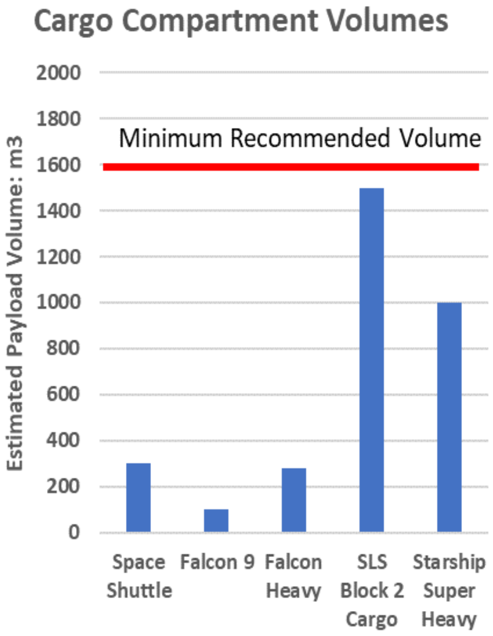


Figure 6 Internal Volume of a Space Elevator Should Exceed that of the Largest Rocket Solution

will be provided later in this paper based on the mission completion timeframe.

Payload Volume – Volume on rockets is of concern to limit aerodynamic drag, center of gravity, and stability and control, Figure 6. The envisioned speed of a space elevator in the atmosphere and the sensitivity of the center of gravity allow the volumes and shaping of a space elevator cargo/personnel compartment to be more customizable for mission needs. It does not have to be cylindrical or evenly dimensioned if other requirements are met. It is suggested that, at a minimum, the ISEC space elevator's internal volume of 1600 cubic meters exceeds that of the largest rocket, Figure 6.

Mission Completion Timeframe – The previous payload recommendation of a minimum of 100 metric tons (MT) for a space elevator was used to ensure a space elevator could deliver payload over the best rockets available or developed and deployed in the not-too-distant future. The question is whether that payload can drastically reduce the timeframe required to complete the missions identified. Figure 7 compares a 100 MT space elevator versus the Falcon 9 Heavy affordable solution. Current ISEC requirements and design solutions continually pursue a system that can launch a space elevator in less than a day. If the launch cycle rate can at least be one launch a day and since there are few limits on the number of launches on the same tether, an assessment was made for one launch and five launches a day. With the heavier lift capacity and significantly increased cycle time, the missions are completed at least ten times quicker than a rocket solution.

Some believe the Moon village should be completed first, and lessons should be learned before proceeding to other settlements, including Mars, various space stations, and asteroid mining operations. All do not share this risk-averse viewpoint, and if the multi-mission capability is desired, then an assessment of accomplishing the Moon village, Mars Colony, and the Space solar power missions at the same time. Suppose a standard timeframe is used, and all missions share the tether. In that case, the space elevator payload is evaluated against the number of launches per day to meet a specific timeframe for completion.

Mission completion timeframes of 5, 10, 15, and 20 years were used to ensure that interested parties would support the development and

Major Off-World Transport Needs - Millions of kg (Mkg)					100 mt Elevator	
	Off-World (Mkg)	# Rockets Falcon Heavy	Years to Complete (1 L/wk)	Years to Complete (5 L/wk)	Years to Complete (1 L/day)	Time to Complete (5 L/day)
Moon Village	500	29,762	572	114	13.7	2.74 years
SpaceX Colony Mars	1,000	59,524	1144	228	27.4	5.48 years
Space Solar Power	5,000	187,000	3596	719	137	27.4 years
L-5 O'Neill Colony	10,500	392,700	7551	1510	287.7	57.54 years
Sun-Earth L-1 Sunshade	20,000	748,000	14384	2876	548	109.6 years
Space Tourism	TBD	TBD				
GEO Manufacturing	TBD	TBD				
Asteroid 3554 Amun Mining Products		Unknown Vehicle				
Other Asteroids & Space Products to Earth		Unknown Vehicle				
Current Total Marketspace Needs	37,000	1,383,900	26,613	5,322	1013.7	202.74

Figure 7 100 MT Space Elevator Mission Completion Timeframe is Over 1/10th of Rockets.

deployment costs only if it would be complete in their lifetime and time horizon. Many other factors will have to be considered. However, the fixed cost associated with a space elevator system and all the other costs of space settlement and space economy development will require tremendous support from wealthy businesspeople and governments that can be incentivized to make space a reality. Previously, the timeframe to complete missions assumed continuous launches every day or week. That is a reasonable assumption for the Moon village and space solar power missions since they are near Earth. However, the Mars mission has traditionally relied upon launch windows to reduce the distance and energy required to travel to Mars. On average, the traditional launch window is approximately two months every two years. Previous ISEC assessments suggest that space elevators can provide alternative launch angles and speeds beyond rockets' usual capability and would not be limited to the traditional launch window. More detail and assessment are required to adopt this as a new operational method.

Figure 8 assesses space railway payload versus cycle times for 5, 10, 15, and 20 years. The solid lines assume the launches are continuous and do not rely on a traditional launch window. As a basis of comparison, the dashed lines assume the Mars mission will use a typical Mars launch window, and to meet the timeframe, the launches are compressed into two months every two years. The dashed line represents the number of launches required for those two months. It is noted that this assumes all use of the tether is outbound only. A tether will bring considerable mass back to Earth if asteroid mining is considered. This will occupy tether time unless more than one tether is deployed. Due to the high fixed cost of a tether and ground station, the economic value of one tether will have to prove itself before additional tethers are built.

A review of the payload versus cycle times suggests that a mission completion timeframe of five or ten years may be too aggressive unless just one mission is pursued. Fifteen- and

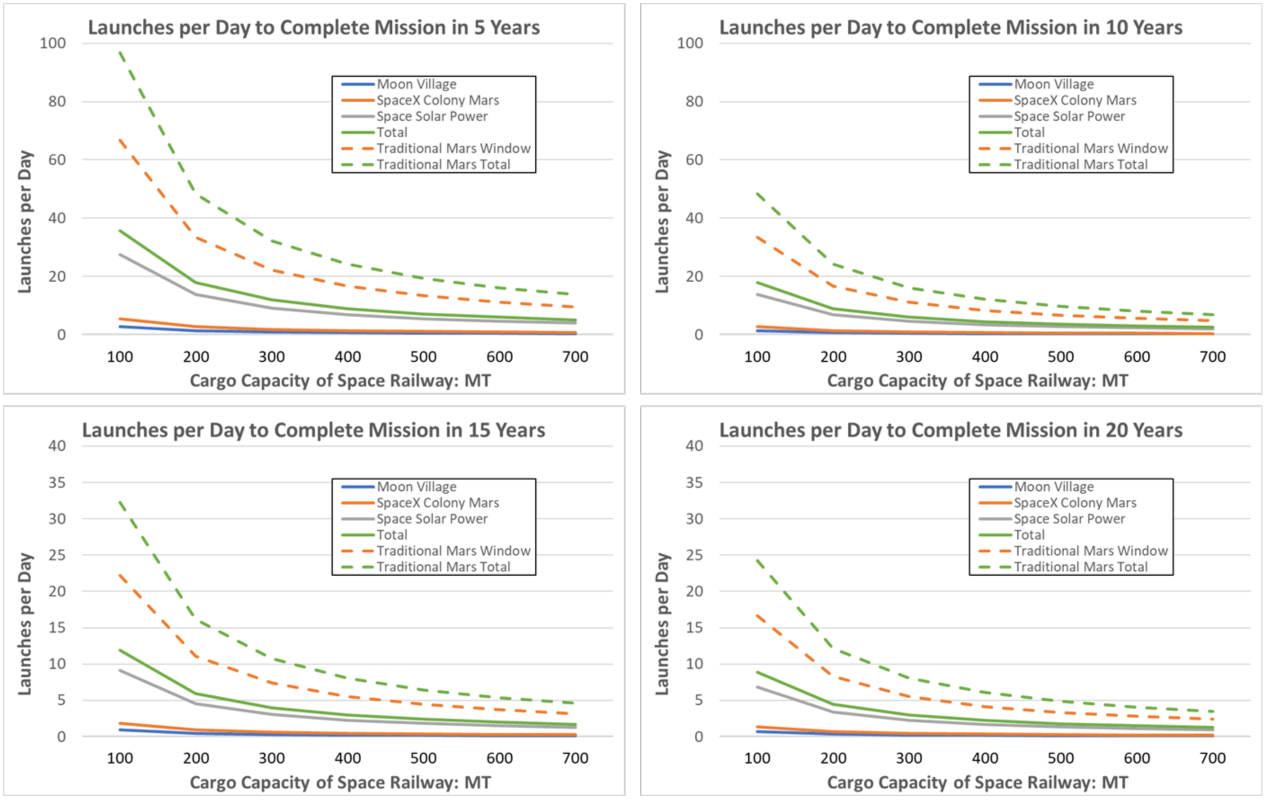


Figure 8 Space Elevator Payload & Cycle Times to Meet a Specific Mission Completion Timeframe

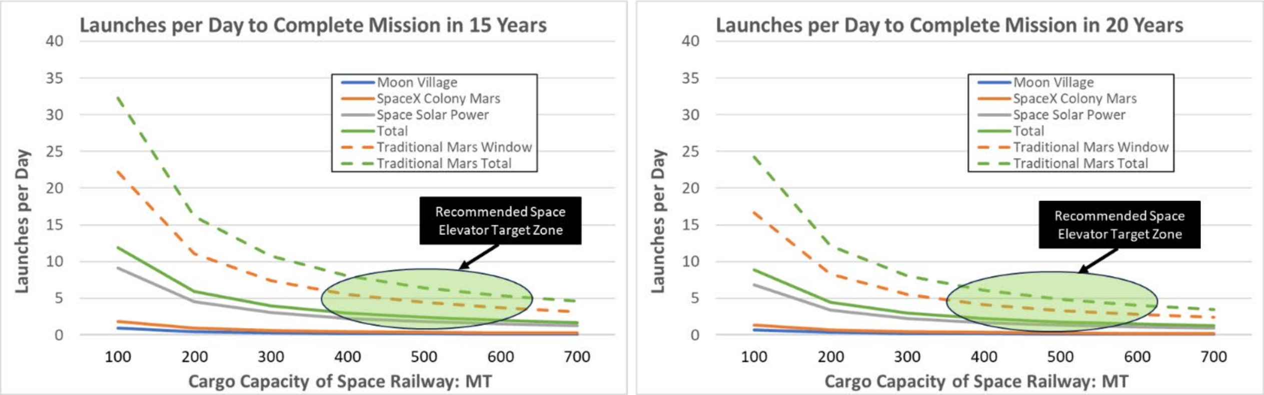


Figure 10 Recommended Space Elevator Targets for Multi-Mission Transportation Needs are in the 400-600 MT Payload Range with Peak Cycles of 5 per day.

twenty-year timeframes appear more manageable based on the number of daily launches if the payload is increased over the previous minimum recommendation of 100 MT. Figure 9 provides a reasonable peak launch cycle time of five daily launches if the payload is between 400-600 MT.

New Requirements Summary

– This assessment aims to answer the question, "If we are serious about settling space and creating a space economy on the order of thousands to millions of people, what will it take from a transportation perspective?" It must be timely, large enough for heavier cargo (e.g., electrically driven Caterpillar track hoe), and have frequent enough launches to deliver people and cargo to a destination to make a serious effort to build a large settlement."

These payloads and cycle times are far beyond current ISEC technology and systems capability. The recommended order of magnitude plus will be challenging and require technological invention. To begin with a reassessment of space elevator requirements and adoption of a meaningful set of requirements that will drive technology development, system, and component design, and provide the economic and business models to interest financial markets and government to fund the various stages of development, deployment, and operation.

Vehicle and system performance has been the focus of this discussion. Another difference that must be addressed is the economics of a space elevator, which is different from rockets, Figure 10. Rockets are mainly a variable-cost business. If required, a space elevator has a tremendous, fixed cost for the tether, ground station, and end-of-tether facility. The space elevator community should continue to work collaboratively through ISEC and focus on the mission cost versus the cost per kilogram, which does not include the fixed cost of the tether. The cost narrative must change since the variable cost-only narrative is only credible for some who conduct a preliminary cost assessment.

It is suggested that the space elevator community and ISEC adopt new requirements to develop technologies in an open environment to meet the real need for relevant, timely,

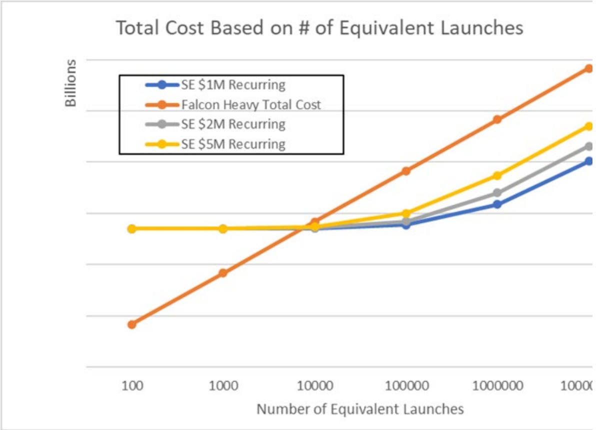


Figure 9 Space Elevator Must have a Low Variable Cost to Compensate for the High Fixed Cost to have an Overall Lower Mission Cost than Rocket Solutions.

meaningful transportation of billions of kilograms of cargo and personnel to GEO and beyond. Top-level performance requirements recommended are:

- Payload capacity of 400-600 MT
- Payload volume minimum of 1600 m^3
- Launch cycles of 5 launches per day
- Rapid Maintenance and Repair considerations for at least a twenty-year tether lifespan
- Total mission cost (fixed plus variable) less than half of a rocket-based solution

Way Forward – Outstanding products and services are created following program and project management processes. Aerospace fully adopted, implemented, and created new processes since the 1980s. ISEC should refocus the space elevator collaborative community on reaffirming the missions and mission needs. Let those drive the requirements of a space elevator. When requirements change as drastically as recommended in this discussion, the concepts, systems, technology, and components will also change. A top-level process going forward is as follows:

- Mission(s) are created
- Requirements are generated to ensure successful mission needs are met
- Concepts are generated that meet the requirements
- Filtering criteria are generated to down-select a preferred concept to pursue, defined as the baseline concept.
- A risk management assessment of the concepts' development is generated, and the appropriate technology development plan is created.
- A risk mitigation plan is developed to reduce the probability of the risk manifesting or reducing the severity of the risk to the overall program.
- The program plan and risk mitigation plan are then executed successfully, or during development, one of the alternative concepts is reassessed as a better solution and becomes the new baseline.

The requirements used for the ISEC open studies need to be updated to reflect an updated view of tethered access to space concepts to provide the undisputed solution for settling space and providing the means of an affordable, timely, large-scale human permanent presence in space. Top-level requirements are recommended, and challenges for the current space elevator design are issued. As this discussion has highlighted, rockets cannot complete the missions envisioned in time. The only non-science fiction solution is to make a space elevator far beyond rockets and those currently pursued under the ISEC collaborative community efforts.

A significant consideration is how to pay thousands or millions of humans to settle and create a permanent society and way of life in space. This assessment concludes that space elevator transport to space is more affordable and can accomplish the mission in a reasonable timeframe compared to rockets. It is still a considerable expense. The question of who will pay is also still being determined. Governments, high-net-worth individuals, corporations, and space enthusiasts are potential sources. Each has its own rationale or business case for allocating funding. It could be personal, geopolitical, investment, or desire to explore reasons.

If some form of payback for allocating funds, whether in total or partial, is required, then some wealth must return to Earth, or the resources sent from Earth must be lessened by obtaining them from space. Mining asteroids and other planets for Earth material and transporting metals, carbon, and water from asteroids or other planets to settlements need to be explored from an economic perspective. Rare Earth elements can return to Earth as payback, and some are retained in space to reduce costs from Earth. Metals, carbon, water, nitrogen, and other elements harvested in space can then be used to sustain life and build structures and equipment.

These various scenarios will place additional transportation requirements on a tether. Bring back or down-Earth payload and volume requirements can be 30,000,000,000 metric tons or more if everything from Asteroid 3554 Amun returns to Earth. The payload and cycle times recommended previously in this paper will have to consider appreciable down-Earth payloads with more considerable cycle time once the space mining operations are in total production.

The author will continue other missions and economic assessments concerning space mining and the space economy. Earth-based economic theory will be assessed for its applicability to the space economy. Modifying theory and new economic theories will assist in understanding investment recovery, individual income, settlement income, and all the various aspects of a capitalist-based economic system. Socialistic and communistic systems do not provide the incentive mechanisms for humans to perform to their utmost.

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