Mission to Mars:

A Comparative Analysis of Rocket Technology and the Space Elevator

Jason Christopher Coe

Embry-Riddle Aeronautical University

ASCI 691 Graduate Capstone

Submitted to the Worldwide Campus

in Partial Fulfillment of the Requirements of the Degree of

Master of Aeronautical Science

December, 2011

Abstract

This study provides an analysis on whether rockets or the space elevator offer the superior method of transportation for a human mission to Mars based on three areas of interest: travel time, safety and cost. The research review examines a broad range of published documents on these topics and focuses on three studies. The first is the rocket-based *Austere Human Mission to Mars* proposal based on the National Aeronautics and Space Administration's Design Reference Architecture 5.0 study. The second and third are studies written by Bradley C. Edwards and commissioned by the NASA Institute for Advanced Concepts. They are entitled *The NIAC phase I report – The space elevator* and *The NIAC phase II report – The space elevator*. Original calculations are presented regarding the travel time, safety and cost of a manned mission to Mars using the space elevator. Then, a comparison is made between rockets and the space elevator using information from both published research and original calculations. The author puts forth that both methods of space travel are similar in terms of travel time and cost, but that the elevator is a better choice in terms of safety and human factors. The author concludes that if the space elevator's developmental hurdles can be overcome, the elevator would emerge as the superior method of transportation for this mission.

Keywords: manned mars mission, space elevator, design reference architecture, austere human mission to mars, rocket technology, space travel

Manned Mission to Mars:

A Comparative Analysis of Rocket Technology and the Space Elevator

Proposal

The purpose of this study will be to analyze whether rockets or the space elevator would provide the superior method of transportation for a manned mission to Mars based on three areas of interest: travel time, safety and cost.

In order to accomplish the objective, a summary of relevant literature and research will be presented on two topics: a chemical rocket-based mission to Mars and the space elevator. Next, the study will focus on original calculations created by the author about travel time, safety issues and cost associated with using the space elevator for a manned mission to Mars, none of which have been previously documented. The research methodology for these calculations will be presented along with a discussion of the results, author's conclusions and recommendations.

Ultimately, the information gathered from the relevant research review and the author's original calculations will be used to compare and contrast chemical rockets to the space elevator in terms of travel time, safety and cost in order to postulate which would provide the better-quality transportation system for a human mission to Mars.

Program Outcomes

PO #1

Students will be able to apply the fundamentals of air transportation as part of a global, multimodal transportation system, including the technological, social, environmental, and political aspects of the system to examine, compare, analyze and recommend conclusion.

A successful manned mission to Mars would be such a significant achievement in space travel that it will have a **global** impact on **air** and **space transportation**. Accomplishing this task will require careful consideration of **technological**, **social**, **environmental** and **political** aspects of the transportation system used. Up to this point, rocket propulsion has been considered the obvious choice of **technology** because it has an extensive, proven history in both unmanned and manned space flight. However, as technologies continue to mature and society becomes more concerned with the **environmental** impacts, transportation methods that are safer and more environmentally-friendly increase in their appeal. The space elevator may provide a more eco-friendly alternative to rocket propulsion. This study will utilize many factors including travel time, safety, and cost to **examine**, **compare**, **analyze** and **recommend** whether rockets or the space elevator would provide the best transportation for a manned mission to Mars.

PO #2

The student will use the techniques and applications from this program and be able to apply the fundamentals of aircraft and spacecraft development, including research and developmental processes, vehicle mission requirements, manufacturing techniques, planning, production, procurement, supply and distribution to solve problems.

Throughout this study, **the fundamentals of spacecraft development** are applied in order to solve problems. This study focuses on two transportation options for a manned mission to Mars, rockets and the space elevator. The **research and development processes** for the space elevator as documented in scholarly articles is reviewed in-depth. The launch **vehicle mission requirements** for both the space elevator and rockets are also examined and compared, in terms of both safety and cost. The **manufacturing techniques** of rockets for this mission is discussed with a focus on how it applies to mission cost control. Additionally, the **manufacturing techniques** of creating the specialized cable required to make the space elevator operable is weighed, including the **supply** of the necessary materials (carbon nanotubes) and the **production** process.

PO #3

The student will be able across all subjects to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including unsafe acts, attitudes, errors, human behavior, and human limitations as they relate to the aviators adaption to the aviation environment to reach conclusions.

Safety is a primary focus of this study. **Human factors** as they relate to safety are specifically considered when weighing rockets against the space elevator. By design, rockets propel themselves and their cargo into space using brute force. Due to this excess thrust, astronauts on board the shuttle experience a sustained 3G load (Main Propulsion, n.d.). Additionally, the rapid gravitational changes resulting from the transition to freefall using rockets disrupt spacial orientation and cause about half of all astronauts to suffer from space sickness (Space travel, n.d.). In this study, calculations are performed and the results indicate that the space elevator reduces the amount of stress placed on humans and spacecraft, and eases astronauts' **adaptation** to the **space environment**. The paper also discusses the **safety factor** selected for the design of the space elevator cable. Failure scenarios, which potentially lead to large-scale industrial accidents and the loss of human life, are also reviewed as part of the safety comparison between the space elevator and rockets.

PO #4

The student will apply current aviation and industry related research and problem solving methods, including problem identification, hypothesis formulation, data gathering, data analysis, and presentation of findings to present as solutions for known problems and scenarios. The student will also use the application of research methodology and analysis in the investigation of an aviation / aerospace related topic, in particular to solve problems from real life case examples.

This study on an **aerospace related topic**, namely a manned mission to Mars, applies **the current research and problem solving methods** utilized for conducting a research project. The introductory portion of this analysis specifically explains the **problem identification** process used by the author (see sections entitled *Background of the problem*, *Statement of the problem*, and *Significance of the problem).* The **hypothesis** presented is that the space elevator, as opposed to rockets, would provide a superior form of transportation to Mars for humans. **Data was gathered** and is presented on both transportation options in terms of travel time, cost and safety using published research and original calculations. This **data is analyzed**, the **findings are presented**, and conclusions are put forth based on the findings.

PO #7,8,11 (Specializations: Operations, Management, Space Studies)

Aviation Aerospace Management

The student will investigate, compare, contrast, analyze and form conclusions to current aviation, aerospace, and industry related topics in management, including aircraft maintenance, industrial safety, production and procurement, international policy, research and development, logistics, airport operations, and airline operations.

Aviation Aerospace Operations

The student will investigate, compare, contrast, analyze and form conclusions to current aviation, aerospace, and industry related topics in operations, including simulation systems, operations research, rotorcraft operations, communication and control systems, air carrier operations, and corporate operations.

Space Studies

The student will investigate, compare, contrast, analyze and form conclusions to current aviation, aerospace, and industry related topics in space studies, including earth observation and remote sensing, mission and launch operations, habitation and life support systems, and applications in space commerce, defense, and exploration.

Managing access to space is a complex initiative that requires the knowledge and application of many disciplines. Specifically, the comparative analysis put forth in this study is a convergence of the three specialized knowledge areas of management, operations and space studies. **Aerospace management** and **operations** knowledge is applied in this study specifically in terms of **budgeting** and **cost analysis**, **industrial safety**, **logistics**, and **operations research**. **Space studies** knowledge is a core focus of this analysis including **mission and launch operations**, and **applications in space exploration**.

Manned Mission to Mars:

A Comparative Analysis of Rocket Technology and the Space Elevator

Historical Background of the Problem

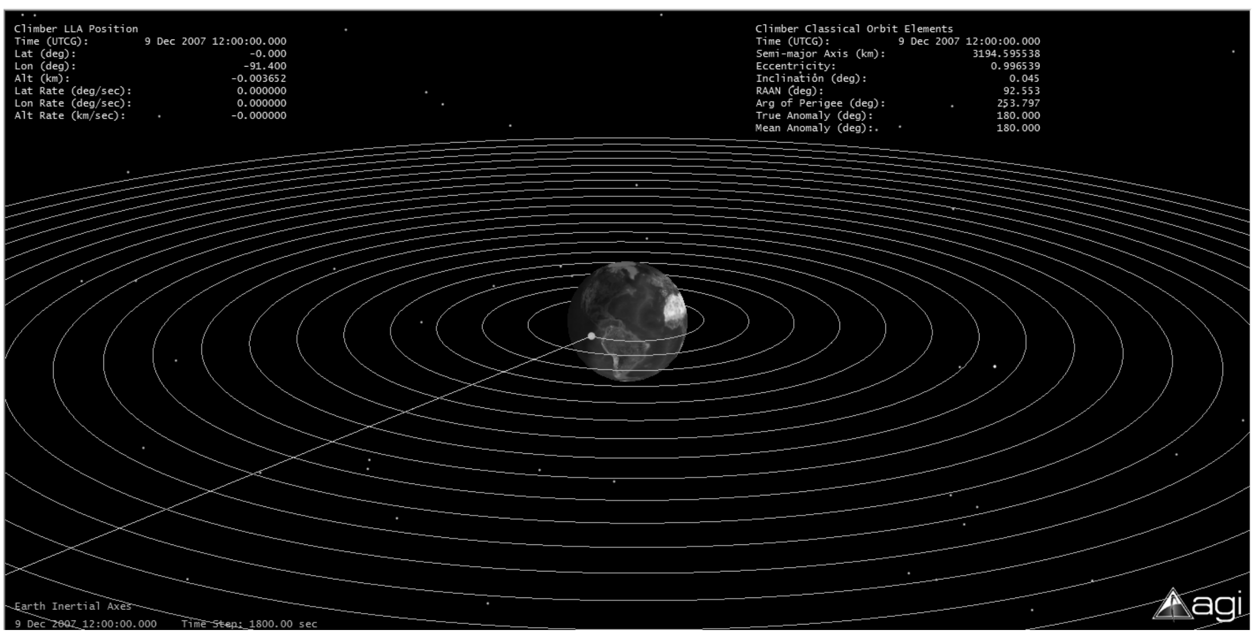
Mars. It is the most Earth-like planet in our solar system, the most readily accessible from Earth. Though humans once had only their imaginations to speculate about the history and composition of the Red Planet, technology has afforded us the ability to differentiate between many of Mars' scientific and science fiction traits. More than 40 years have passed since the first successful robotic spacecraft mission to Mars, and since then there have been numerous flyby, orbiter and lander missions – some successful, and many not (Historical Log, n.d.). All of these missions provide a wealth of information, both about the planet itself as well as the business of travelling to Mars. Yet, there remains much more to be learned about Earth's most compatible neighbor.

Man's desire for this knowledge coupled with our seemingly unquenchable urge to explore space has made a manned mission to Mars a primary ambition for space exploration. Because such a feat has yet to be accomplished, there are many challenges and questions inherent to this mission. Perhaps the most important question is: *How do we get there?* While rocket-based technology has been the prevalent choice for human space exploration, a new contender is getting a lot of attention: the space elevator.

The concept of the space elevator was born in the late 1800s, with credit given to Konstantin Tsiolkovsky, a Russian rocket scientist who envisioned a tower reaching from the ground into space (Bellis, n.d.). While conceptually intriguing, the idea of travelling to space on a fixed tower was thought to be physically impossible until contemporary science and technology began to provide solutions that could turn this theory into reality.

Simply stated, the modern concept of the space elevator describes a system in which a cable is anchored to Earth and extends upward beyond the atmosphere to a point in space where centrifugal force causes the cable to be pulled taut. With this cable in place, the transportation vehicle, or climber, attaches to the cable and *climbs* it into space (Edwards, 2000, 2003). See Figure 1. Researchers hypothesize that the velocity present at the end of the cable would make it possible to launch a space craft off of the cable, propelling it far beyond the orbit of Earth (Edwards, 2000, 2003). While an operable space elevator has yet to be built, researchers commissioned by the National Aeronautics and Space Administration (NASA) have examined the concept in-depth. Many believe that this new technology could be the future of space travel.

Figure 1: Image of space elevator showing path through space.



Model created using AGI’s STK software. STK® is a mission-proven software application for modeling, engineering and operations of space, cyberspace, C4ISR, UAVs, missile defense and electronic systems. (www.AGI.com) *Note:* Original work by Author.

Statement of the Problem

Several governments including the United States, China, Russia and the European Space Agency have expressed interest in pursuing a manned mission to Mars making this a global endeavor (Zey, 2010). In addition to public entities, private organizations like MarsDrive, an international non-profit space organization, have joined the race. As a result of this interest, there exists a variety of proposals for accomplishing this goal. A few examples include the *Austere Human Missions to Mars* (based on NASA's Mars Design Reference Architecture V study), Mars Society Germany's *European Mission to Mars*, and most recently the *Hundred Year Starship Initiative* proposed by NASA Ames Research Center Director, Pete Worden, in 2010.

Research reveals that as technology advances, the ability to create a functional space elevator could be in the not too distant future (Edwards, 2000, 2003). Therefore, it is wise to also consider this new technology as an option for a human mission to Mars. However, proposals such as those previously mentioned focus on the current and future technology of rocket-based missions. This is likely attributed to the fact that the space elevator has yet to be built; therefore, the research conducted on the elevator to this point focuses largely on the feasibility of building an operational elevator. Not much information beyond speculation has been published about the use of the space elevator for manned missions.

Significance of the Problem

Mankind's interest in space exploration has not waned, and new technologies continue to revolutionize this industry. Therefore, it is important to persist in our research of these new technologies. Theorizing and examination will enable us to determine if man can create a faster, safer and less expensive form of space travel. The space elevator could be the end result, and ultimately open up the solar system for future exploration – to Mars and beyond. In fact, in today's environmentally conscious society, a system that utilizes the natural motion of the earth as a basis for space travel could be viewed as a more socially-acceptable and preferred method of space transportation.

Purpose of the Study

The purpose of this study is to analyze whether rockets or the space elevator would provide the superior method of transportation for a manned mission to Mars based on three areas of interest: travel time, safety and cost. In order to accomplish this, a summary of relevant literature and research is presented on two topics: a chemical rocket-based mission to Mars and the space elevator. Next, the study focuses on calculations created by the author to make determinations about travel time, safety issues and cost associated with using the space elevator for a manned mission to Mars, none of which have been previously documented. The research methodology for these calculations is presented, with the subsequent sections discussing the results, author's conclusions and recommendations.

Ultimately, the information gathered from the relevant research review and the author's original calculations is used to compare and contrast chemical rockets to the space elevator in terms of travel time, safety and cost in order to postulate which would provide superior transportation for a human mission to Mars.

Limitations

Two primary limitations exist in this study. First, a successful manned mission to Mars has not been accomplished, nor has any party attempted this goal. An abundance of scientific research is available regarding travel to Mars due to prior missions of flyovers, orbits and landers. However, it must be acknowledged that none of these missions carried humans, so unknown variables exist pertaining specifically to manned missions. In order to limit further unknowns associated with a manned mission to Mars, the present analysis utilizes information and strategies based on current rocket technology, specifically the chemical rocket, as opposed to postulating about futuristic rocket technology.

Second, the fact that a functional space elevator does not yet exist is a major limitation. Because of this, assumptions have to be made about the elevator, though significant scientific research has been conducted which provides a concrete, if only conceptual, understanding of how the elevator would perform. Due to its theoretical nature, equations applied to the calculations within this study are simplified to gain a general understanding. The assumptions that are built into the calculations are discussed in the section on research methodology.

Assumptions

As previously stated, several proposals currently exist for accomplishing a human mission to Mars using rocket-based technology. In order to compare the use of rockets to the space elevator in terms of travel time, safety and cost of travelling to Mars, it was necessary to select one proposal on which to focus. The proposal commissioned by NASA in 2007, titled the *Mars Design Reference Architecture 5.0* (DRA 5), might seem to be the natural choice given that NASA is generally considered to be the authority on space travel in the United States and beyond. However, this proposal calls for the development of nuclear thermal rocket technology as a propulsion system. Because this system has not yet been developed, the DRA 5 does not provide cost estimates for this mission. Furthermore, there are many additional unknown variables inherent in this proposal because the technology is not currently in use.

In order to remedy this problem, this analysis is based on a proposal published in 2009, titled *Austere Human Mission to Mars*, hereafter referred to as “the Austere Mission.”

According to the authors, "Most of the elements of this paper were taken from the DRA 5 study…The impetus behind the austere architecture is to offer an approach that might have lower development cost, lower flight cost, and lower development risk" (Price, Hawkins & Radcliffe, 2009, p. 2). The Austere Mission accomplishes this in a number of ways, most notably by using a smaller crew with fewer trips, and avoiding the development of new technology, specifically, utilizing chemical rockets instead of nuclear thermal rockets (Price, et al, 2009). As a result of this strategy, the Austere Mission proposal puts forth a very detailed description of their suggested program to travel to Mars, including information needed to compare the use of rockets to the space elevator in this study. Therefore, the assumption is made for this study that the information set forth in the Austere Mission proposal is scientific and reliable, and provides a sound platform for comparing rockets to the space elevator.

In regards to the space elevator, there have been various writings on the topic, but two reports are considered to be the primary source of current research and information. These two reports were written as the result of grants awarded by the NASA Institute for Advanced Concepts (NIAC) and are titled *The NIAC Phase I Report: The Space Elevator* and *The NIAC Phase II Report: The Space Elevator* (Edwards, 2000, 2003). Edwards' reports explain in the detail the space elevator's design, potential challenges, costs and much more.

Edwards' work (2000, 2003) is considered by scholars to be the most thorough source for a scientific assessment of the elevator. His publications are used in this study as a primary means of understanding how the space elevator would perform if used for a human mission to Mars. Therefore, the second assumption made in this study is that the information set forth in Edwards' two reports on the space elevator is scientific and reliable, albeit often theoretical.

Method

Review of Relevant Literature and Research

Chemical Rockets: Austere Human Mission to Mars.

Background information. Commissioned by NASA headquarters in 2007, the goal of the Mars Architecture Working Group was to develop documentation to describe the systems and operations necessary to carry out the first three human exploration missions to Mars. The result of the commission was the DRA 5. The DRA 5 outlines a plan for NASA to send humans to Mars in the 2030 time frame using Constellation Program elements (Drake, 2009).

In 2009, Hoppy Price, a NASA Jet Propulsion Laboratory employee, along with Alisa Hawkins and Torrey Radcliffe of The Aerospace Corporation, published a document entitled Austere Human Mission to Mars. The goal of this study was to create an architecture for a human mission to Mars that offered a lower development cost, lower flight cost, and lower development risk than the plan outlined in the DRA 5. While their approach does not meet all of the mission requirements of the DRA 5, it proposes a mission that would meet the basic scientific and space exploration goals with less risk and lower cost (Price, et al, 2009).

The Austere Mission deviates from the DRA 5 in its recommended propulsion technology. The Austere Mission chose chemical propulsion over the proposed nuclear thermal rocket (NTR) technology presented in the DRA 5. NTR technology has yet to be established for this use, thus, using NTRs would increase the development cost and risk of the project (Price, et al, 2009). Alternatively, chemically powered rockets have been used for decades and have been the propulsion system of choice for the United States Space Program, most recently powering the Space Transportation System to low earth orbit (LEO) through the use of solid rocket boosters and a large external tank (Main Propulsion, n.d.).

The Austere Mission calls for two trips to Mars, each with a four-person crew to be sent every four years. It proposes the use of a single platform design for all landed elements and a common Earth departure configuration. This re-use of technology facilitates efficiency in design and production, drives down costs through mass production, and reduces the number of tests required to validate a system (Price, et al, 2009).

Travel time. In order to provide the lift required to place all necessary elements in a low earth parking orbit, the Austere Mission calls for the use of yet to be developed Ares V heavy lift rockets (Price, et al, 2009). Low earth parking orbits are the preferred starting position for missions departing the influence of Earth for two primary reasons. Parking orbits provide a location for crew and controllers to verify that all systems are working as anticipated before committing to the final transfer. Parking orbits also provide more potential launch windows (Apollo Expeditions, n.d.). The Ares V, successor to the Saturn V, which was responsible for delivering man to the moon, was to be developed as part of the Constellation Program and would have an estimated lifting capacity of 188 tons to LEO (Coffey, 2009). Even with the massive lift capacity of the Ares V, a complete mission would require twelve unique launches. Eight of the launches are needed to lift the rocket propulsion systems necessary to take the three cargo landers and the Mars transit habitat from LEO to Mars.

Because the Austere Mission uses chemical rockets, the path to Mars would likely use the Hohmann Transfer. The Hohmann Transfer is "an elliptical transfer orbit tangent to the initial and final orbits" and provides the most fuel efficient way to transfer orbits (Sellers, 2005, p. 94). Using this route, the trip to Mars from LEO takes approximately 8.5 months (Stern, 2004).

Safety. From a perspective of safety, chemical rockets have a proven track record. In the history of United States manned space missions, only one has been fatal due to a rocket malfunction when an o-ring in the right solid rocket booster failed causing the Space Shuttle Challenger to explosively decompress 73 seconds after launch on January 28, 1986 (Ryba, 2007).

The Austere Mission proposal examines multiple potential failure scenarios. In the event that the Descent/Ascent Vehicle failed prior to deorbit at Mars, the crew could remain in the Transfer Habitat until an opportunity to return to Earth arose (Price, et al, 2009). Without the abundant power provided by the Surface Power and Logistics Module, a full duration mission could still be accomplished. However, experiments and off-site discovery would be limited. The failure of the Surface Habitat would create a scenario in which a short-duration mission could be accomplished by living in the two pressurized rovers. In the event that both the Surface Habitat and the Surface Power and Logistics Module failed, a brief mission, comparable to that of the Apollo lunar missions, could be completed (Price, et al, 2009).

Budget estimates. The Austere Mission puts forth that if the United States chooses to develop and fund the proposed austere program without outside contribution, the estimated cost with a 50% contingency over 18 years is approximately $75 billion (Price, et al, 2009). Refer to Table 1. Development, testing, and two flights to Mars are included in this budget (Price, et al, 2009).

Table 1

Budget Estimates for the Austere Mission to Mars

Notional cost profile for major program elements for an all-U.S. program.

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	Total
Descent/Ascent Vehicle (DAV)	dvmt.	500	1,000	1,500	2,200	2,500	2,000	500												10,200
Earth Departure Stage (EDS)	dvmt.	200	300	400	600	500	400	200												2,600
Ares V upgrade	dvmt.	300	400	600	600	600	300	200												3,000
DAV test flight	test						500	1,500	1,390											3,390
TransHab Development	dvmt.				200	400	600	600	700	500	400	300								3,700
MOI/TEI Stage	dvmt.					200	300	400	600	600	400	200								2,700
CEV upgrade	dvmt.							200	200	200	200	200								1,000
TransHab test flight	test									504	1,008	504								2,015
SurfHab Development	dvmt.					300	300	700	750	800	750	750	350							4,700
Power/Logistics Module	dvmt.					200	400	500	700	750	550	400	300							3,800
SurfHab	Flt. 1												851	1,703	851					3,405
Power/Logisitics Module	Flt. 1												920	1,840	920					3,680
DAV	Flt. 1														848	1,695	848			3,390
TransHab/Crew	Flt. 1														633	1,265	633			2,530
SurfHab	Flt. 2																851	1,703	851	
Power/Logisitics Module	Flt. 2																920	1,840	920	
DAV	Flt. 2																		848	
TransHab/Crew	Flt. 2																		633	
Reserves/margin (50%)		500	850	1,250	1,800	2,350	2,400	2,400	2,170	1,677	1,654	1,177	1,211	1,771	1,626	1,480	1,626	1,771	1,626	25,055
Total ($M)		**1,500**	**2,550**	**3,750**	**5,400**	**7,050**	**7,200**	**7,200**	**6,510**	**5,031**	**4,961**	**3,531**	**3,632**	**5,314**	**4,877**	**4,440**	**4,877**	**5,314**	**4,877**	**75,165**

Note: Price, H., Hawkins, A. M., & Radcliffe, T. O. (2009). *Austere Human Mission to Mars*. American Institute of Aeronautics and Astronautics. (p.16)

The Space Elevator.

Background information. In 1960, Russian engineer Yuri Artsutanov modernized the concept of an elevator into space. Artsutanov's vision of an "electric rocket" had many of the pieces that were detailed in later conceptualizations of the space elevator, including the use of a ribbon design for the cable (Artsutonov, 1960). However, he did not analyze the feasibility of such a system or how it would actually work with existing or future technologies.

Jerome Pearson, an engineer and current President of Star Technology and Research, Inc, served as a project engineer and branch chief for the Air Force Research Laboratory for 26 years (Star Technology, n.d.). Pearson, who was at the time an engineer at the United States Air Force Flight Dynamics Laboratory, released a report on the space elevator (1975). In this study, Pearson became the first to explain the science behind the actual cable on which the climber would travel.

At the time of Pearson's study, the only existing substance that could potentially provide a workable taper ratio were perfect-crystal whiskers of graphite, and their strength-to-weight ratio was only theoretical. Even if the cable could have been built utilizing graphite whiskers, the estimated weight of the final cable would have required approximately 720,000 shuttle flights to geosynchronous orbit (GEO) in order to assemble it properly (Pearson, 1975).

Pearson is credited with determining important information about the cable's design. According to Pearson, "The balanced tower has a maximum tensile force at the synchronous balance point, and this tensile force decreases toward the ends. In order to minimize the weight of the tower, its cross-sectional area should be tapered as a function of the gravitational and inertial forces to maintain a constant stress" (1975, p. 787). This taper ratio is important because the stress placed on the cable is not uniform and reaches its maximum at GEO. Using this knowledge, the proposed construction of the tower would begin at GEO while simultaneously extending outward and inward. Pearson wrote, "This would have the effect of replacing the maximum compressive stress at the base by the same maximum stress in tension at the synchronous point" (1975, p. 788).

Modern concept and design. In 2000, the NASA Institute for Advanced Concepts (NIAC), an independent body commissioned to further the advancement of space research, awarded physicist and researcher Bradley C. Edwards with multiple grants to study the space elevator based on current, sound scientific principles. Edwards' research culminated in the release of two NIAC reports, titled The Space Elevator: Phase I (2000) and The Space Elevator: Phase II (2003). In these reports, Edwards identified four distinct components of the modern conceptual space elevator. These include the anchor, cable, climber and propulsion system. His findings are summarized below.

The *anchor* is the point on Earth to which the cable is tethered. The anchor station is a mobile, ocean-going platform similar to ones used in oil drilling yet customized for the specific needs of providing a stabile power beaming station and housing up to 100 staff for long periods of time. The suggested location for the anchor is approximately 1000 miles west of the Galapagos Islands. This location was selected based on weather, mobility, and the fact that the rotational velocity of Earth is greatest at the equator (Edwards, 2000). Detailed wind, weather, and wave studies were performed and found to be within tolerances of a sea launch platform (Edwards, 2003).

The space elevator must be able to avoid collisions with on-orbit satellites. In the Phase 1 report, Edwards suggests that the ocean-going anchor move up to one kilometer, thus moving the cable in order to avoid a collision with space junk, meteorites, or satellites. The anchor moves linearly along the equator and then back to its original spot, thus sending a “pulse” up the cable. A move in the opposite direction is used to eliminate the pulse, resulting in a quiet system (Edwards, 2003).

The *cable* is the transportation medium that extends from the anchor to a point in space where a counterweight is secured. Edwards suggests construction using carbon nanotubes (CNTs), a newly discovered form of carbon whose strength is much greater than steel, as shown in Table 2 (Edwards, 2000). However, at this time it is not yet possible to produce CNTs possessing the precision and length necessary to build a cable for the elevator, nor are CNTs being produced at a rate to meet the demand for this project. It is estimated that the creation of material strong enough for the space elevator is five to ten years away (Dunn, 2009).

Table 2

Comparison of Properties of Steel, Kevlar and Carbon Nanotubes

	Steel	**Kevlar**	**Carbon Nanotubes**
Tensile Strength	<5 GPa	3.6 GPa	130 GPa
Density	7900 kg/ m^3	1440 kg/ m^3	1300 kg/m^3
Taper Ratio	1.7 x 10^{33}	2.6 x 10^{8}	1.5

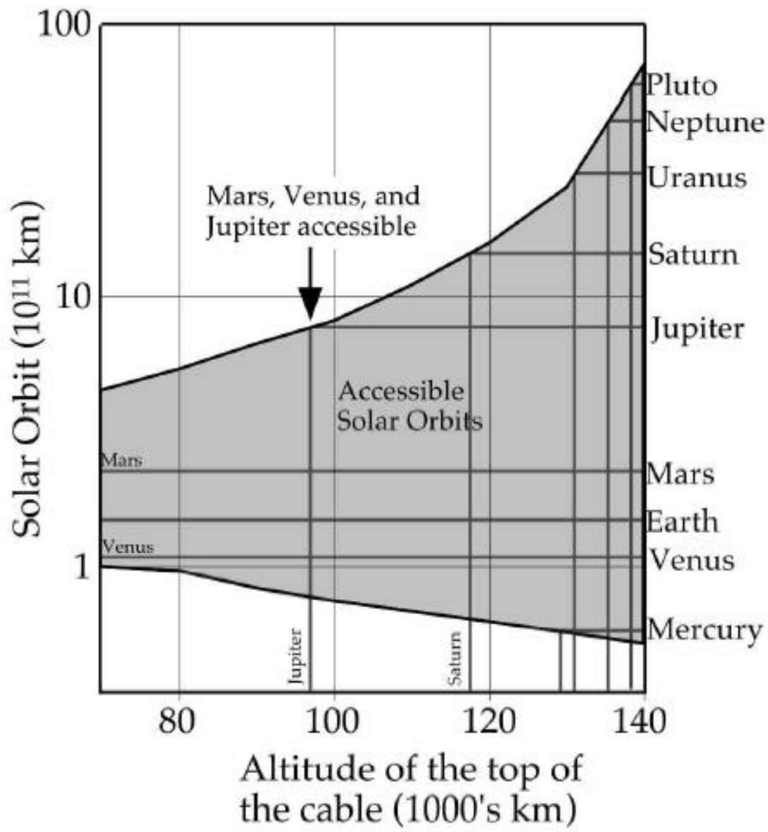
Note: From Edwards, B.C. (2000)

The Phase II report includes knowledge gained about the composite production, degradation methods, and available materials for constructing the cable. Although both reports indicate the optimal design of the cable as a ribbon, the detailed construction is refined in Phase II, ultimately producing a more robust structure (Edwards, 2003).

Edwards offers two methods of cable deployment. The first option is to park at GEO and send out cable in both directions, with the center of gravity maintained at GEO. The second uses a single direction cable with an outward moving counterbalance (Edwards, 2000). The initial report suggests standard rocket propulsion systems launch the initial cable and machinery to LEO, where they are assembled into a larger package to be migrated to GEO for deployment (Edwards, 2003).

As a trade-off between cable mass and the potential for interplanetary travel, Edwards uses the equation for the conversion of momentum and energy to determine destinations available in Earth's equatorial plane. At a length of 91,000 km, Mars, Venus and Jupiter are accessible, as shown in Figure 2 (Edwards, 2000).

Figure 2: Destinations available to the space elevator by cable length.



Note: From Edwards, B. C. (2000, October). *The NIAC phase I report: The space elevator*. (p.7.2)

The third aspect of the space elevator is the *climber*, which is the transportation vehicle that scales the cable to any potential orbit. According to Edwards, the climber can be built using current satellite technology. It would have a drive system built with DC electric motors, photovoltaic cells and a power conditioning system (Edwards, 2000).

Finally, a laser *propulsion system* delivers the power necessary to the photovoltaic arrays on the climber (Edwards, 2000). Edwards' study refers to the laser design built for the Stanford Accelerator Complex (SLAC), the best laser built at that time. This laser technology is upgradeable and when combined with a 15 m diameter beam director is capable of producing a beam that would be ten times more intense than that of the Sun, yet would work in the confines of an ocean-going anchor and be safe for birds and airplanes through which to fly (Edwards, 2003) .

Travel time. Edwards estimates that initial climbers would ascend at a rate of 200 km per hour, taking 7.5 days to reach GEO. A full strength cable is capable of supporting a 22 ton climber, of which 14 tons is payload. For payloads heavier than one climber can support, multiple trips are needed to assemble the final payload. However, it is not necessary to for one climber to return before launching another. Climbers can be launched every 4 days (Edwards, 2000).

If mission elements are launched to Mars using the Hohmann Transfer, travel time from the point at which the climber is released from the cable is approximately the same as a rocket-based mission launched at the same time, specifically, about 8.5 months, because spacecraft travelling via the Hohmann Transfer travel at the same velocity in orbit around the Sun (Stern, 2004).

Safety. When designing safety into the cable, Edwards chose a safety factor of two. As with any proposed safety factor, Edwards made trade-offs between the probability of a catastrophic cable failure and what is possible to build. This design decision provides for a cable that is theoretically twice as strong as it minimally needs to be in order to support the maximum amount of weight and survive the environmental challenges it would face including induced currents, radiation exposure, atomic oxygen, severe weather, and meteors. Edwards' design also recommends that climbers be equipped with a release mechanism triggered by a climber from below (Edwards, 2000).

Budget estimates. In his Phase I report, Edwards provides an estimated budget for the space elevator based on his research. His budget estimates are organized into two categories:

fixed costs, which address the cost to build the first elevator, and operating costs, which address ongoing operational expenses. As there is very little existing infrastructure in place that could effectively support the space elevator, a significant investment in building the elevator is required. All fixed costs are based on known or current pricing estimates, except for ribbon production, because this is under development, and climbers, because a working model of the cable is first required. The total fixed cost of building the elevator with a 100% contingency is approximately $40 billion. The total fixed costs of building a second cable is $14.3 billion (Edwards, 2000).

The per-year operating budget assumes a payload capacity of 14 tons per launch, a staff of 280 people, and 50 launches per year. This results in a total of approximately $135 million annually, or $250 per kg cost to any destination (Edwards, 2000). The budget estimates are summarized in Table 3.

Table 3

Budget Estimates for the Space Elevator

FIXED COSTS	
Component	**Estimated Cost ($US billion)**
Launch to GEO (7)	3.7
Ribbon Production	5.0
Spacecraft	1.0
Climbers (207)	4.2
Power Beaming Station (2)	2.2
Power Generating Station	0.4
Anchor Station	0.3
Tracking Facility	1.0
10-year operation	1.56
Contingency (100%)	20
TOTAL	**~ 40 BILLION**

Note: Summarized from Edwards, BC. (2000)

OPERATING COSTS (Per Year)	
Component	**Estimated Cost ($US million)**
Climbers	0.2 – 2 each
Tracking System	10
Anchor Station	10
Administration	10
Anchor Maintenance	5
Laser Maintenance	20
Other	30
TOTAL (50 launches)	**135 MILLION**
($250/kg operating costs to any destination)	

Summary and Statement of the Research Question

The above literature and research review presents scholarly findings about a rocket-based, human mission to Mars in terms of travel time, safety and cost. While scientific information has been published on the space elevator, much less has been documented about the space elevator in terms of a manned mission to Mars. As a result, original research is required in order to compare chemical rockets to the space elevator. The section on research methodology explains how the author examines travel time, safety issues and costs associated with a manned mission to Mars using the space elevator. The subsequent findings enable one to address the primary research question of this study, which is: *Would rockets or the space elevator provide the best option for a manned mission to Mars in terms of travel time, safety issues and cost?*

Research Methodology

Introduction. To make determinations about the travel time, safety issues and costs associated with a manned mission to Mars in the space elevator, calculations were computed using Excel. The results are shown in Appendix B. Calculations are based on a snapshot in time at a specific altitude. Altitude is the shared value among all equations. In order to generate the calculations, several variables were used and are illustrated in Table 4.

Table 4

Calculation Variables

Calculation Variables	
Climber ascent speed (km/hr)	200
Earth's Mean Radius (meters)	6.3781×10^{6}
Time Interval (hours)	2
Gravitational Constant ($N \cdot m^2/kg^2$)	6.6742×10^{-11}
Earth's Mass (kg)	5.9736×10^{24}
mu- Earth (km^3/s^2)	3.978×10^{24}
Sidereal Day (hours)	23.9344696
Earth rotation (radians/sec)	7.29×10^{-5}

Travel time. The journey to Mars on the space elevator involves two distinct trips. First, the climber travels from Earth's surface to a point on the climber at which it is released, called the *release point*. It is at this point on the cable that the elevator has enough excess velocity to depart the sphere of influence of Earth and enter into a transfer orbit to Mars (Edwards, 2000. 2003). During the second part of the trip, the climber travels from the release point to Mars. As discussed previously, it is known that by utilizing the Hohmann Transfer, the elevator reaches the orbit of Mars approximately 8.5 months after being released (Stern, 2004).

Travel time from Earth to the release point is found by dividing the distance to the release point by the speed of the elevator.

Travel time = altitude of release point / elevator speed

The location of the release point, and thus, the travel time for the trip from Earth to the release point, is not yet known, and therefore needs to be calculated. To find the release point, two calculations are needed, namely Delta V boost and Delta V potential.

Delta V boost (ΔV_{boost}) is dependent on the altitude above Earth and is calculated by finding the positive difference between the spacecraft's velocity on the hyperbolic-escape trajectory at the parking orbit radius ($V_{hyperbolic}$) and the spacecraft's velocity in the circular parking orbit (V_{park}) around Earth. $V_{hyperbolic}$ is equal to the square root of two times mμ divided by the mean radius of Earth plus the current altitude plus the spacecraft's energy on its hyperbolic-escape trajectory. V_{park} is equal to the square root of mμ divided by the mean radius of Earth plus the current altitude (Sellers, 2005).

$$\Delta V_{boost} = \left| V_{hyperbolic} - V_{park} \right|$$

Delta V potential ($\Delta V_{potential}$) in this study, refers to surplus velocity the climber experiences as it ascends to an altitude above the point where horizontal velocity exceeds escape velocity. Prior to this point, no excess velocity is available to escape the sphere of influence of Earth. This calculation is performed by subtracting escape velocity (V_{escape}) from horizontal velocity ($V_{horizontal}$) at the given altitude.

$$\Delta V_{potential} = V_{horizontal} - V_{escape}$$

Safety. To address safety issues specific to the space elevator, four measurements are considered: Earth's gravitational force applied to the climber, artificial gravity due to centrifugal force, and the relationship between escape velocity and the climber's horizontal velocity. These calculations provide information about the external influences placed on the climber by its position relative to Earth and the velocity experienced by the climber aboard the cable. Ultimately they aid in determining if the space elevator is safe for human travel. The formulas are outlined below.

Gravitational force (F) equals the gravitational constant (G) multiplied by the mass of Earth (M), divided by Earth's mean radius (R) plus the current altitude. The mass of the climber is miniscule compared to that of Earth. Since the climber is ascending, the radius is constantly changing and can be found by adding the current altitude to Earth's mean radius.

$$F = GM / (R + \text{current altitude})$$

Artificial gravity (a) is calculated by squaring the rotation of Earth (W) in radians per second, and multiplying that by the distance of the climber from the center of Earth (r). The climber is always in motion; it climbs the cable, and until it is released, it rotates in space at the same rate as Earth. This rotation and distance from the center of Earth creates a virtual force called centrifugal force, or artificial gravity.

$$a = W^2 r$$

Escape velocity (v_e), technically a scalar, is the speed in which an object “frees” itself from a gravitational field. To calculate escape velocity above Earth’s surface, the formula is based on the gravitational constant (G), Earth’s mass (M), and the distance from the center of Earth (r), which will change as the climber ascends the cable.

The current escape velocity (V_e) is calculated by taking the square root of the gravitational constant (G) multiplied by Earth’s mass (M), divided by the distance from the center of Earth (r). The distance from the center of Earth is calculated by adding the current altitude above Earth to Earth’s mean radius.

$$v_e = \sqrt{\frac{2GM}{r}}$$

Climber’s horizontal velocity (V_h) above Earth’s surface is calculated by using the circumference of the orbit ($2\pi r$) divided by the time it takes Earth to make one complete rotation (sidereal day). As the climber ascends the cable, the radius is constantly increasing. The results are shown in Appendix B both in km per hr and km per sec. To convert to km per sec, the total is divided by 3600.

$$V_h = 2\pi r \text{ / length of sidereal day}$$

Cost. There are five essential cost components for a human mission to Mars using the space elevator (Edwards, 2000). These include building and operating the elevator, developing the mission-specific elements, launching the mission-specific elements, and mission operation costs. In his report, Edwards provides budget estimates for the development and annual operation costs of the space elevator (Table 3). The unknown costs include the development of mission-specific elements, launching those elements, and mission operation costs.

The mission-specific elements for Mars are estimated using the Austere Mission's budget, which specifies the development costs of these components. This includes the descent/ascent vehicle, transit habitat, crew exploration vehicle, surface habitat, and power/logistics module. The total mass of these elements is calculated and multiplied by the space elevator's per kg cargo launch costs in order to estimate launch expenditures. Finally, operation costs specific to this mission are estimated by analyzing those of the Austere Mission budget and applying the same amount to the elevator.

Assumptions. The following assumptions are made for the calculations in this analysis:

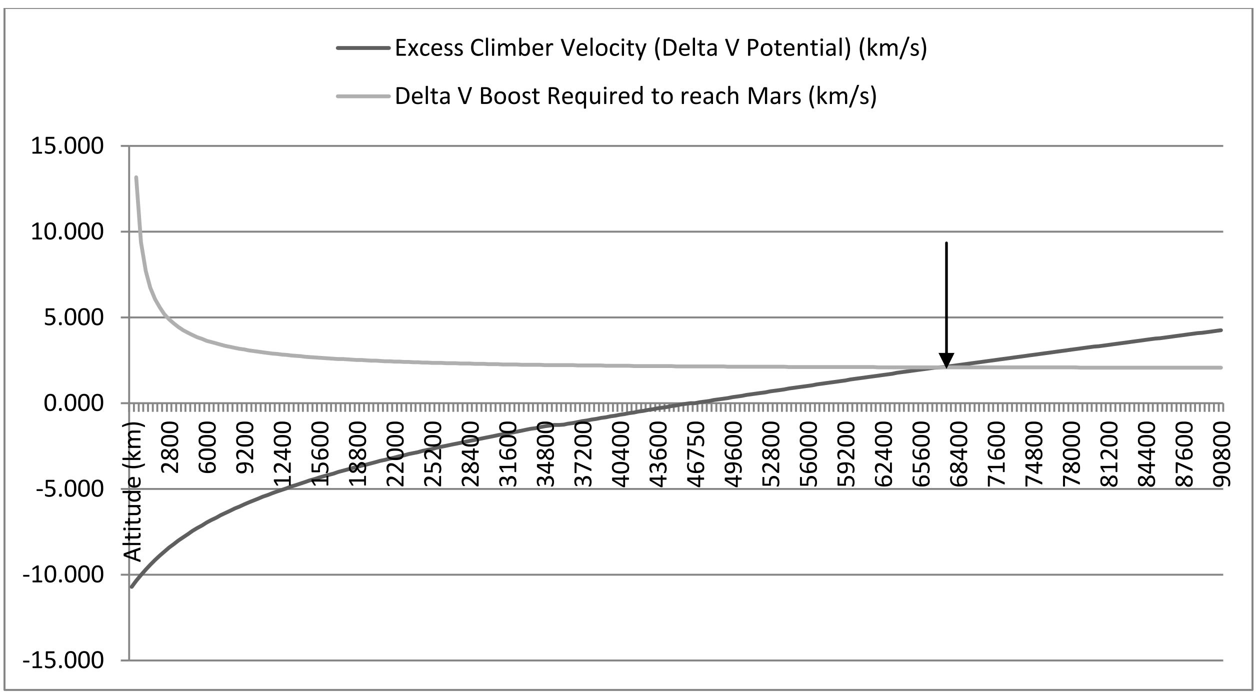
- The strength of the cable is such that it safely supports a 20 ton climber from the surface of Earth to the end of the cable.
- The cable remains in a vertical orientation perpendicular to the surface of Earth at all times.
- The climber has the capabilities of accelerating to and maintaining a velocity of 200km/hr.
- The propulsion system can deliver the needed energy to the climber in order to maintain a constant velocity at any point on the cable.
- The braking system on the climber has sufficient capacity to keep the full weight of the object at a velocity of 200 km/hr beyond GEO.
- The calculation for Delta V boost is based on a transfer orbit to Mars.
- For gravitational force calculations, the effects of Earth's rotation are disregarded.
- No perturbations are taken into account.

Results

Travel Time

Travel time from Earth to the release point is estimated by dividing the distance to the release point by the speed of the elevator. To find the release point location, Delta V boost and Delta V potential are calculated at each altitude. The altitude where they equal each other is the point at which the climber has enough excess velocity available to reach Mars using the Hohmann Transfer. The release point is located at an altitude of 67,400 km and is shown in Figure 3. Assuming a constant speed of 200 km/hr, the elevator reaches the release point in 337 hours or 14.04 days.

Figure 3: Release Point: Intersection of Delta V boost and Delta V potential

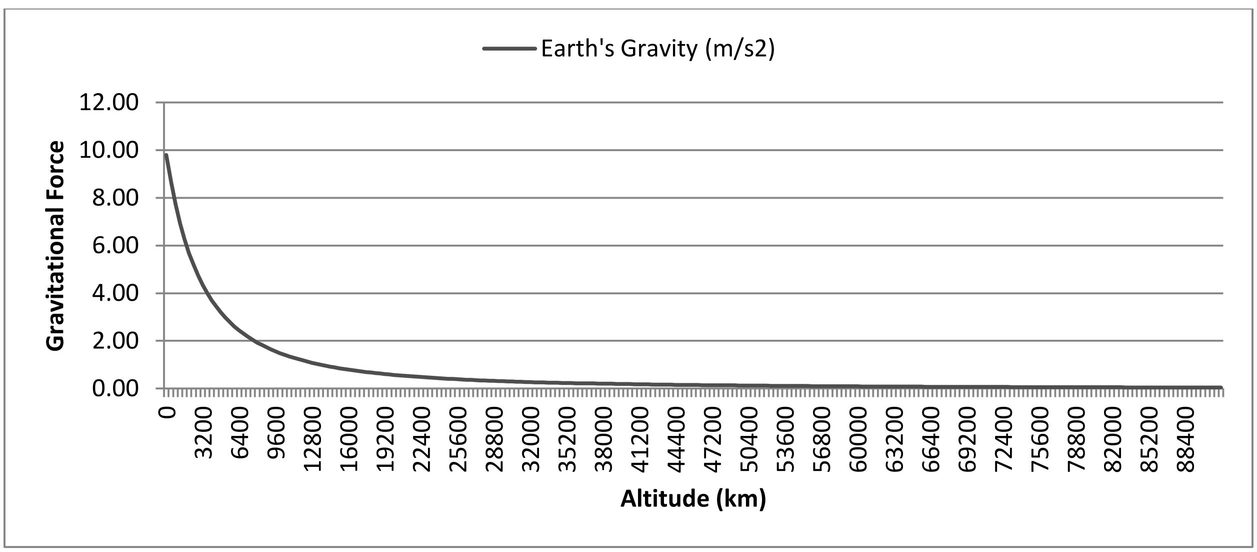


Safety

To address safety issues specific to the space elevator, four measurements are considered: the Earth's gravitational force applied to the climber, artificial gravity due to centripetal force, and the relationship between escape velocity and the climber's horizontal velocity.

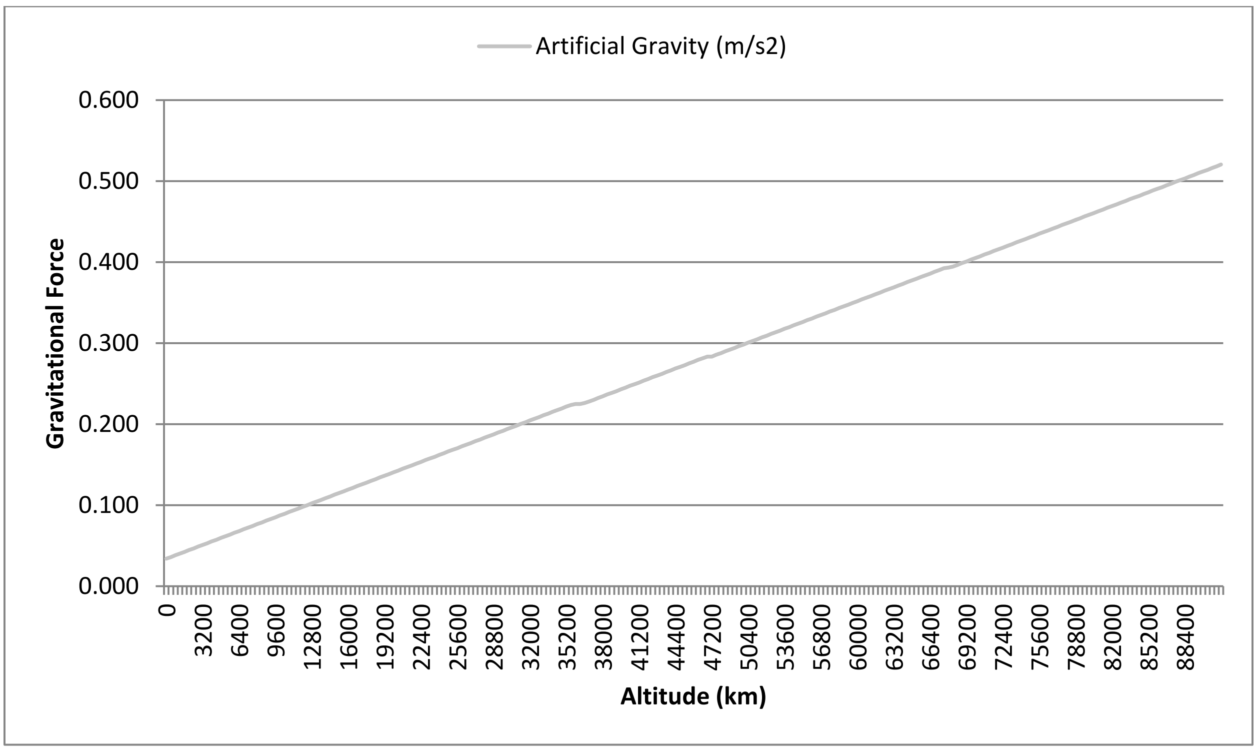
Gravitational force. At approximately 2000 km above Earth, a maximum altitude for low earth orbit, the climber and its occupants complete only 2% of a journey to the end of the cable, yet they experience a weight loss of 42% (See Appendix B). At 9600 km, roughly 11% of the full length of the cable, occupants weigh 84% less than on Earth. The time to each of these points is 10 hours and 48 hours, respectively, much longer than it takes for a traditional rocket-based mission to reach similar altitudes. See Figure 4.

Figure 4: Gravitational force on the space elevator as it ascends



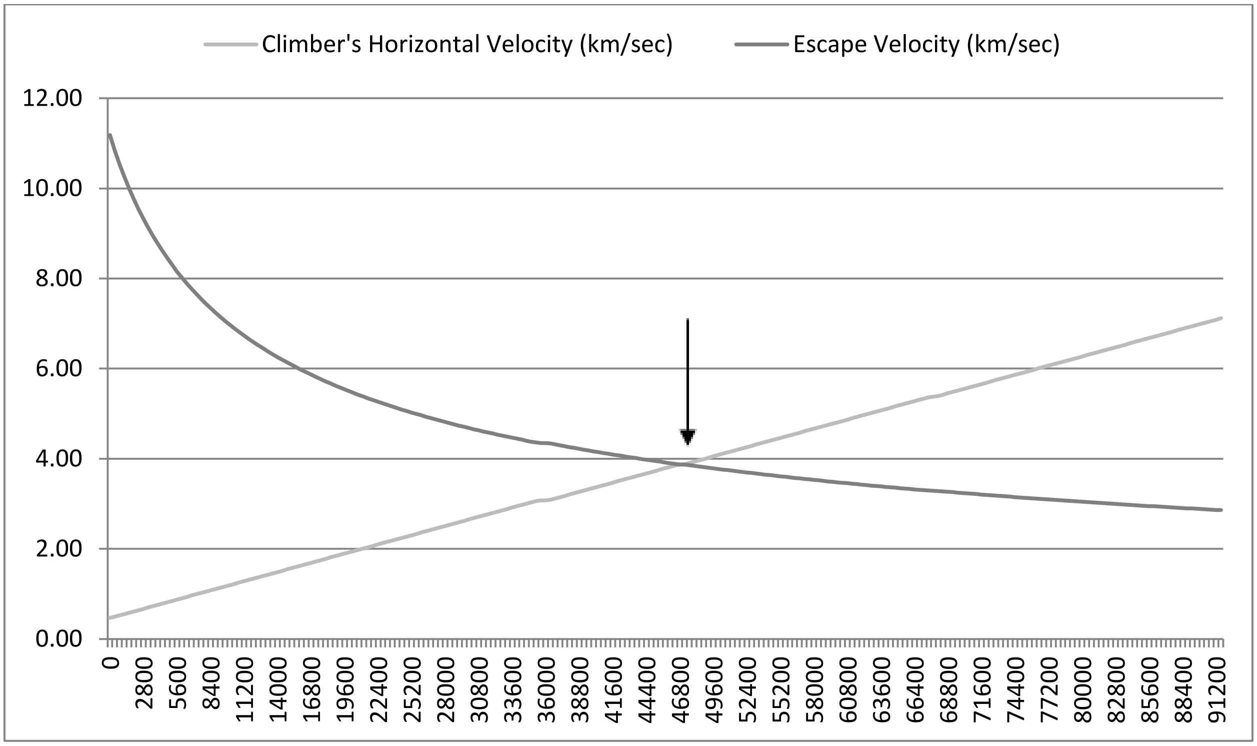
Artificial gravity. The space elevator climber, like any mass rotating about a central point, experiences artificial gravity as it ascends the cable, as depicted in Figure 5. Until it reaches GEO, the net effects are offset by the force of gravity from Earth. After GEO, artificial gravity increases and the gravitational effects of Earth decrease resulting in a net increase in artificial gravity. The results show that at the end of the 91,000 km cable the total force on the climber, and subsequently any objects in or on the climber, experience approximately 1/20th of the force of gravity present on Earth.

Figure 5: Artificial gravity experienced by the space elevator as it ascends



Relationship between escape velocity and climber's horizontal velocity. If the climber intentionally or accidentally detaches from the cable at or beyond the point where horizontal velocity exceeds escape velocity, it would no longer be in Earth's sphere of influence. Departure from the cable beyond this point puts the climber on a Sun-focused orbit unless sufficient thrust is available to reduce velocity and bring it back into orbit around Earth. Without thrust capabilities, this is essentially the point of no return for the climber. This point is located at an altitude of 46,750 km. See Figure 6.

Figure 6: Point of no return: Intersection of Earth's escape velocity and climber's horizontal



Cost

There are five essential cost components for a manned mission to Mars using the space elevator. These include building and operating the elevator, developing the mission-specific elements, launching the mission-specific elements, and mission operation costs. The Austere Mission does not include in its budget the costs of any scientific research or projects that might be conducted during the Mars mission, so neither does this analysis of the space elevator.

Edwards provides estimates for the price to build and operate the space elevator (Table 3). The price to build is $40 billion plus an annual operating cost of $135 million. The mission-specific elements for the Mars mission are estimated using the Austere Mission's budget, which specifies the development costs of these components to be $23.4 billion, shown in Table 5 (Price, et al, 2009).

TABLE 5

Cost of Mission-Specific Elements for Mars

Component	Estimated Cost ($US billion)
Descent/ascent vehicle	10.2
Transit habitat	3.7
Crew exploration vehicle	1.0
Surface habitat	4.7
Power/logistics module	3.8
TOTAL	**23.4 BILLION**

Note: Summarized from Price, et al. (2009) p. 27

The mass of the mission elements as detailed in the Austere Mission proposal is approximately 664,400 kg on Earth (Price, etc al, 2009). These are itemized in Table 6. This total does not include the eight rockets required to complete the Hohmann Transfer in the Austere Mission, which are not needed when using the space elevator.

TABLE 6

Mass of Launch Cargo

Cargo	Estimated Mass in Metric Tons	Conversion to Kilograms
MAV cabin & propulsion	45.9	
MAV lander descent stage	119.3	
Cargo lander payload (habitat)	52.0	
Cargo descent stage (habitat)	114.4	
Cargo lander payload (surface power & logistics)	52.0	
Cargo descent stage (surface power & logistics)	114.4	
Crew exploration vehicle (CEV)	10.0	
Transit habitat	35.0	
Contingency module	7.0	
MOI/TEI module	114.4	
TOTAL	**664.4**	**664,400**

Note: Summarized from Price, et al. (2009) p. 22

The per kilogram launch cost of the space elevator is estimated at $250 per kg to any point on the cable (Edwards, 2000). The cost to launch the 664,400 kg of mission-specific elements as cargo is $166.1 million. Because the mission calls for two flights, the total cost is $332.2 million.

Operation costs specific to this mission are difficult to estimate because no direct research is available. However, the total budget for the Austere Mission is known to be about $75 billion, $26 billion of which is allocated for two flights ($13 billion per). It is also known that the launch cost estimates to LEO for Ares V rockets are approximately $7,000 per kg (Bess, Colvin and Cummings, 2009), and the total weight of the Austere Mission cargo is 664,400 kg per flight. This totals $4.65 billion in launch costs per flight to LEO, which accounts for 36% of the total Austere Mission flight budget of $26 billion. It can be extrapolated that $16.7 billion in the Austere Mission budget accounts for the mission operation cost of two flights. Therefore, this study estimates the mission operation cost for the elevator to be the same, specifically, $16.7 billion for two flights.

The total estimated cost for a manned mission to Mars using the space elevator with the components detailed above is $80.84 billion and is summarized in Table 7.

TABLE 7

Estimated Total Cost of Mission to Mars via the Space Elevator

Space Elevator Components	**Estimated Cost ($US billion)**
Space elevator development	40.0
Annual operating expenses ($135m for 3 yrs)	0.41
Mission-specific elements development	23.4
Mission-specific elements launch ($166.1m for 2 flights)	0.33
Mission operational costs (2 flights)	16.7
TOTAL	**80.84 BILLION**

Discussion

Travel Time

The journey for both chemical rockets and the space elevator to Mars via the Hohmann Transfer is approximately 8.5 months. However, there are additional time considerations to take into account. Firstly, according to the author's calculations, the elevator travels about 14.1 days to reach the release point where it can access the Hohmann Transfer. It takes rockets only about 10.5 minutes to reach parking orbit, the location from which a rocket can initiate the Hohmann Transfer.

Secondly, the Austere Mission proposal calls for 12 rocket trips to carry all of the mission elements to parking orbit where they are assembled prior to departing for Mars. The total mass of elements as identified in the Austere Mission is 664 tons on Earth (Table 6). According to the specifications that Edwards provides, the space elevator is capable of carrying only 14 tons of cargo, much less than rockets. To carry 664 metric tons to any destination, the elevator requires a minimum of 48 trips, many more than the 12 necessary for rockets in the Austere Mission. Furthermore, most of the elements described in the Austere Mission weigh more than 14 tons a piece. This means that the elements would require a redesign in order for the elevator to carry them to orbit to be assembled.

However, Edwards also puts forth that an elevator can be launched every four days (2003). According to the calculations on the effects of gravitational force as the climber ascends, the elevator reaches 19,200 km in four days where 14 tons of cargo weighs the equivalent of 1743 lbs, or six percent of their weight on Earth. This likely prevents the necessity of 48 individual roundtrips to carry the 664 metric tons of cargo. Instead, multiple climbers utilizing the cable at the same time could carry pieces to undergo final assembly in orbit. This strategy is similar to the batching method in the Austere Mission plan that uses 12 rocket trips to carry all mission elements into space to be assembled.

Safety

The force of gravity on Earth (1G) is equivalent to 9.8 m/s^2 and is an important factor in spacial orientation in humans (Science Daily, 2008). During a shuttle launch, astronauts experience approximately three Gs of force, resulting in a weight three times that on Earth. Ten minutes later when the shuttle reaches LEO, astronauts in freefall encounter weightlessness. These rapid gravitational changes disrupt spacial orientation and cause about half of all astronauts to suffer from space adaptation syndrome (SAS), or *space sickness* (Space travel, n.d.). The brain typically adjusts to the new environment in a few days and symptoms subside (Science Daily, 2008).

Though a rocket-powered shuttle reaches LEO in about 10 minutes, the elevator reaches LEO in approximately 10 hours. On the space elevator, the human body does not undergo the same rapid change of one G on Earth, to three Gs during launch, to freefall. Furthermore, humans on a space elevator lose only 42% of gravitational force at LEO, whereas astronauts in a shuttle are in freefall. This phenomenon occurs because the space elevator climbs vertically and travels horizontally at the same rate as Earth, as opposed to a shuttle that travels horizontally at the 17,500 miles an hour needed to maintain a low earth orbit. Because the transfer to freefall takes substantially longer for the space elevator, the loss of gravity is spread out over time which might ease the detrimental effects of rapid gravity loss.

In regards to artificial gravity, it was found that beyond GEO it is present on the space elevator climber, whereas it is not on a rocket-powered shuttle in orbit. At the end of the 91,000 km cable, the total force on the climber and any objects in or on the climber experience approximately 1/20th of the force of gravity present on Earth. In freefall the body goes through significant changes, such as fluids shifting and loss of bone density. The presence of artificial gravity on the space elevator beyond GEO could lessen the adverse effects of weightlessness (Space travel, n.d.). However, the risks involved through excess Delta V would far outweigh any biological benefits to be gained at that altitude.

The point of no return is used to describe the altitude at which the climber is no longer in Earth's sphere of influence. If the climber detaches from the cable at or beyond this point, it begins a Sun-focused orbit. The point of no return is found to be at an altitude of 46,750 km. However, the release point, which is the location that the climber leaves the cable to initiate the Hohmann Transfer and travel to Mars, is beyond the point of no return, at 67,400 km. Therefore, there are 20,650 km, or 4.3 days, where the climber is at increased risk for an aborted mission. It is therefore necessary to equip the climber with the ability to reduce velocity, likely using thrusters.

Cost

The Austere Mission's estimated cost is $75.165 billion, which includes the development and testing of all mission elements, plus two complete manned flights to Mars (Table 1). It also includes a 50% contingency. The Austere Mission depends on the development of the Ares V rocket, which was cancelled along with the Constellation Program (Malik, 2010). The NASA Authorization Act of 2010, which ended development of Ares V, granted NASA the right to design a shuttle-derived, heavy lift launch vehicle called the Space Launch System (SLS). The Act authorized $6.9 billion over three years for SLS development (NASA, 2011). The actual cost to make the SLS a reality is unknown, but NASA reports in regards to the SLS, "The reference vehicle design does not appear to be affordable within expected budget levels" (NASA, 2011, p. 14). Therefore, it is likely that the Austere Mission would come in over budget now that the Ares V will not be available.

As detailed in the research section, there are five essential cost components for a manned mission to Mars using the space elevator. These include building and operating the elevator, developing the mission-specific elements, launching the mission-specific elements, and mission operation costs. The total for these components is estimated at $80.84 billion (Table 7). This includes the 100% contingency Edwards' built into his estimates for building the elevator.

With a total mission cost of $75.165 billion for the Austere Mission, at face value the Austere Mission proposal using rockets appears to be less expensive. However, many assumptions are built into the estimates for both the space elevator and the Austere Mission, so it must be acknowledged that the range of error is significant enough that the opposite could be true. Additionally, ambitious space exploration projects such as a manned journey to Mars have a reputation for coming in over budget. The 100% contingency may not be enough for the space elevator, just as a 50% contingency may be inadequate for the Austere Mission's rocket mission.

Conclusions

The space elevator appears to require more trips to carry cargo into space to be assembled, and these trips take much longer than on a rocket. As a result, the time required to ready the mission elements for the journey to Mars is likely longer for the space elevator. Additionally, the elevator adds 14 days to the 8.5 month long trip to Mars for the astronauts.

From a safety perspective, the gravitational force and artificial gravity present on the space elevator potentially provide a more suitable environment for humans. Yet, the point of no return for the climber is located 20,650 km before the release point. Therefore, four days of the

14-day journey on the cable are higher risk; though equipping the elevator with thrust capabilities could prevent it from being catastrophic.

With the research and information available it is difficult to be certain whether the cost to use the space elevator for a manned mission to Mars or a rocket-based mission is lower. It might be deduced, though, that the costs are similar.

In conclusion, it appears that travel time and cost for the space elevator and a rocket-based mission to Mars are comparable, and the journey would likely be milder on the elevator. However, there exist many unknowns for the development and space exploration capabilities of the space elevator. If the developmental hurdles accompanied with the space elevator could be overcome, and if the price tag were in line with a rocket-based mission, the elevator would emerge as the superior method of transportation for a manned mission to Mars.

Recommendations

Additional research is needed to determine if travel time to Mars in the space elevator could be decreased. This study assumes that 200 km per hour is the elevator's fixed speed. However, as the elevator ascends and the effects of gravity weaken, the elevator loses much of its weight, so it may be able to climb faster. Additionally, this study assumes that the space elevator would initiate the Hohmann Transfer at the defined release point. Yet, if the climber travels further out on the cable before releasing, it would travel at a higher rate of speed, shortening the time spent in a transfer orbit, though it would require a large retro thrust to prevent it from flying past the orbit of Mars.

Further scientific analysis should be conducted to verify that the elevator is safe for human travel. This is not examined by Edwards in his studies, nor has any other author put forth a scientific analysis on the topic.

Several options are available for a return trip if the space elevator is used for a manned mission to Mars. However, this issue necessitates its own analysis and is not included in this study. In order to devise a complete plan for sending humans to Mars on the elevator, the return trip must be considered.

References

Artsutanov, Y. (1960, July 31). To the cosmos by electric rocket. *Pravda*. Retrieved August 11, 2011, from http://www.spacequotations.com/Artsutanov_Pravda.pdf

Bellis, M. (n.d.). *Konstantin Tsiolkovsky*. Retrieved August 5, 2011, from http://inventors.about.com/library/inventors/blrocketTsiolkovsky.htm

Bess, J., Colvin E., & Cummings, P. (2009, June 14). NTR-Enhanced lunar-base supply using existing launch fleet capabilities." *Idaho National Laboratory*. ANS Annual Meeting. Atlanta.

Coffey, J. (2009, December 22). Ares V. *Universe Today*. Retrieved August 14, 2011, from http://www.universetoday.com/47983/ares-v/

Delft University of Technology (2008, May 21). Why Do Astronauts Suffer From Space Sickness?. *ScienceDaily*. Retrieved August 22, 2011, from http://www.sciencedaily.com-/releases/2008/05/080521112119.htm

Drake, B. G., ed. (2009, July). *Human exploration of Mars: Design reference architecture 5.0*. NASA-SP-2009-566. National Aeronautics and Space Administration. Retrieved August 13, 2011 from http://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf

Dunn, J. (2009, January 18). "Space elevator…and the next floor is outer space." *The Times*. Retrieved August 13, 2011, from http://www.timesonline.co.uk/tol/driving/features/article5529668.ece

Edwards, B. C. (2000, October). *The NIAC phase I report: The space elevator*. NASA Institute for Advanced Concepts. Retrieved July 17, 2011 from http://www.niac.usra.edu/files/studies/final_report/472Edwards.pdf

Edwards, B. C. (2003, October). *The NIAC phase II report: The space elevator.* NASA Institute for Advanced Concepts. Retrieved July 17, 2011, from http://www.niac.usra.edu/files/library/meetings/annual/jun01/521Edwards.pdf

NASA. (n.d.). *Apollo expeditions to the moon: An all up test for the first flight*. Retrieved August 15, 2011, from NASA's site: http://history.nasa.gov/SP-350/ch-3-4.html

NASA. (n.d.). Historical Log. *Mars Exploration Program.* Retrieved August 5, 2011, from NASA's Jet Propulsion Laboratory Mars Exploration Program Web site: http://mars.jpl.nasa.gov/programmissions/missions/log/

NASA. (n.d.). *Main propulsion system*. Retrieved August 12, 2011, from Kennedy Space Center Web site: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-mps.html

NASA. (2011, January). *Preliminary report regarding NASA's Space Launch System and Multi-Purpose Crew Vehicle*. Retrieved August 21, 2011, from NASA's site: http://www.nasa.gov/pdf/510449main_SLS_MPCV_90-day_Report.pdf

Malik, T. (2010, October 11). *President Obama signs new vision for U.S. space exploration into law*. Retrieved August 21, 2011, from Space.com at http://www.space.com/9305-president-obama-signs-vision-space-exploration-law.html

Pearson, J. (1975). The orbital tower: a spacecraft launcher using the Earth's rotational energy. *Acta Astronautica. Sept/Oct 1975*(2), 785-799. Pergamon Press.

Price, H., Hawkins, A. M., & Radcliffe, T. O. (2009). *Austere Human Mission to Mars*. American Institute of Aeronautics and Astronautics. Retrieved August 12, 2011, from http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/41432/1/09-3135.pdf

Ryba, J. (2007, November 23). Space shuttle mission archives: Challenger. Retrieved August 15, 2011, from *National Aeronautical and Space Administration's* site: http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/archives/sts-51L.html

Sellers, J. J. (2005). *Understanding space: An introduction to astronautics*. (3rd ed.). New York, NY: The McGraw-Hill Companies.

Space travel 101: Fundamentals of space travel. (n.d.). Retrieved August 21, 2011, from *Think Quest* site at: http://library.thinkquest.org/03oct/01581/SpaceTravelEnglish/dangers/spaceadaptation.html

Star Technology and Research, Inc. (n.d.) Jerome Pearson's Resume. *Star, Inc*. Retrieved August 12, 2011, from http://www.star-tech-inc.com/bios/jeromepearson.html

Stern, D. P. (2004, December 12). *From stargazers to starships.* Chapter #21B: Fly to Mars! Retrieved August 18, 2011, from NASA Goddard Space Flight Center's site: http://www-istp.gsfc.nasa.gov/stargaze/Smars1.htm

Zey, M. (2010, June 7). *As US Abandons Manned Flight, China, Russia, Europe Train For Space Colonization with Mars500*. Retrieved August 22, 2011, from http://www.examiner.com/future-trends-in-national/as-us-abandons-manned-flight-china-russia-europe-train-for-space-colonization-with-mars500

Tables

Table		Page
1	Budget Estimates for the Austere Mission to Mars	17
2	Comparison of Properties of Steel, Kevlar and Carbon Nanotubes	20
3	Budget Estimates for the Space Elevator	23
4	Calculation Variables	24
5	Cost of Mission-Specific Elements for Mars	33
6	Mass of Launch Cargo	33
7	Estimated Total Cost of Mission to Mars via the Space Elevator	34

Figures

Figure		Page
1	Image of Space Elevator Showing Path Through Space Using AGI STK Software	9
2	Destinations Available to the Space Elevator by Cable Length	21
3	Release Point: Intersection of Delta V Boost and Delta V Potential	29
4	Gravitational Force on the Space Elevator as it Ascends	30
5	Artificial Gravity Experienced by the Space Elevator as it Ascends	31
6	Point of No Return: Intersection of Escape Velocity and Climber's Horizontal Velocity	32

Appendix A

Definition of Terms

Artificial gravity – Simulated gravity created by the rotation of a mass around a central point. (Dictionary.reference.com)

Chemical rocket – Rockets propelled as a result of the combustion of a fuel and an oxidizer, such as hydrogen and oxygen. (Sellers, 2005)

Delta V (ΔV) – Instantaneous velocity change measured by the amount of effort it takes to carry out an orbital maneuver, typically provided by the thrust of an engine. (Sellers, 2005)

Delta V boost (ΔV_{boost}) – The velocity change a spacecraft must generate to go from its parking orbit around Earth onto its hyperbolic-departure trajectory. (Sellers, 2005)

Delta V potential ($\Delta V_{potential}$) – The surplus velocity experienced by a space elevator climber as it ascends to an altitude above the point where horizontal velocity exceeds the rotating body's escape velocity. (Author)

Escape velocity – The minimum speed that an object at a given distance from a gravitating body must have so that it will continue to move away from the body instead of orbiting it. (dictionary.reference.com)

Geosynchronous orbit (GEO) – An inclined orbit with a period of about 24 hours. A subset of geosynchronous orbit known as geostationary orbit, also known as GEO, has a period of about 24 hours and rotates around the equator. (Sellers, 2005)

Gigapascal (GPa) - A metric unit of pressure used in this study to express the tensile strength of a material. Equivalent to 1.5×10^5 pounds per square inch. (dictionary.reference.com)

Gravity - The tendency for objects to be attracted to one another. Newton's Law of Universal Gravitation states that the force of attraction between any two masses is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. Newton estimated the gravitational constant (G) to be 6.67×10^{-11} N m^2 kg^{-2}. (Sellers, 2005)

Hohmann Transfer – A fuel-efficient way to transfer between orbits, as theorized by German engineer, Walter Hohmann, in 1925. Uses an elliptical transfer orbit tangent to the initial and final orbits. (Sellers, 2005)

Low earth orbit (LEO) – An orbit with an altitude generally accepted to be between 80 and 2,000 km.

Nuclear thermal rocket (NTR) – Uses a nuclear reactor to heat a propellant, such as liquid hydrogen. The superheated propellant then expands through a nozzle producing high thrust. (Sellers, 2005)

Perturbation- A term used in astronomy to describe alterations to an object's orbit caused by gravitational interactions with other bodies. (Sellers, 2005)

Safety factor – A multiplier used to reduce the chance of failure. (Sellers, 2005)

Speed – A scalar value measuring the rate of motion. (dictionary.reference.com)

Velocity - Measurement of the rate and direction of change in the position of an object. (Sellers, 2005)

Appendix B

Author's Original Calculations

Climber Ascent Speed (km/hr)	200	Time Interval		2	Earth's Mass (kg)	5.974E+24	Earth rotation (Θ/sec)		7.29212E-05
Earth's Mean Radius	6.378E+06	Gravitational Constant		6.674E-11	mμ - Earth	3.987E+14	Sidereal Day (hours)		23.9344696
Altitude (km)	**Time (hrs)**	**ΔV Hyperbolic (km/s)**	**ΔV park (km/s)**	**Δ V Boost Required to reach Mars (km/s)**	**Climber's Horizontal Velocity (km/sec)**	**Earth Escape Velocity (km/sec)**	**Excess Climber Velocity (ΔV Potential) (km/s)**	**Earth's Gravity (m/s^2)**	**Centrifugal Force (m/s^2)**
0	0				0.47	11.18	-10.716	9.80	0.034
400	2	44.74	31.57	13.1724	0.49	10.85	-10.352	8.68	0.036
800	4	31.70	22.32	9.3825	0.52	10.54	-10.016	7.74	0.038
1200	6	25.94	18.23	7.7164	0.55	10.26	-9.705	6.94	0.040
1600	8	22.51	15.78	6.7307	0.58	10.00	-9.416	6.26	0.042
2000	10	20.18	14.12	6.0630	0.61	9.76	-9.145	5.68	0.045
2400	12	18.46	12.89	5.5738	0.64	9.53	-8.891	5.17	0.047
2800	14	17.13	11.93	5.1964	0.67	9.32	-8.652	4.73	0.049
3200	16	16.06	11.16	4.8945	0.70	9.12	-8.426	4.35	0.051
3600	18	15.17	10.52	4.6463	0.73	8.94	-8.212	4.00	0.053
4000	20	14.42	9.98	4.4378	0.76	8.77	-8.009	3.70	0.055
4400	22	13.78	9.52	4.2599	0.79	8.60	-7.815	3.43	0.057
4800	24	13.22	9.11	4.1058	0.82	8.45	-7.631	3.19	0.059
5200	26	12.73	8.76	3.9709	0.84	8.30	-7.454	2.97	0.062
5600	28	12.29	8.44	3.8516	0.87	8.16	-7.286	2.78	0.064
6000	30	11.90	8.15	3.7452	0.90	8.03	-7.123	2.60	0.066
6400	32	11.54	7.89	3.6498	0.93	7.90	-6.968	2.44	0.068
6800	34	11.22	7.66	3.5635	0.96	7.78	-6.818	2.30	0.070
7200	36	10.93	7.44	3.4851	0.99	7.66	-6.673	2.16	0.072
7600	38	10.66	7.24	3.4135	1.02	7.55	-6.534	2.04	0.074
8000	40	10.41	7.06	3.3479	1.05	7.45	-6.399	1.93	0.076
8400	42	10.18	6.89	3.2874	1.08	7.35	-6.268	1.83	0.079
8800	44	9.96	6.73	3.2316	1.11	7.25	-6.141	1.73	0.081
9200	46	9.76	6.58	3.1798	1.14	7.15	-6.018	1.64	0.083
9600	48	9.58	6.44	3.1317	1.17	7.06	-5.899	1.56	0.085
10000	50	9.40	6.31	3.0868	1.19	6.98	-5.783	1.49	0.087
10400	52	9.24	6.19	3.0449	1.22	6.89	-5.670	1.42	0.089
10800	54	9.08	6.08	3.0056	1.25	6.81	-5.560	1.35	0.091
11200	56	8.93	5.97	2.9688	1.28	6.74	-5.453	1.29	0.093
11600	58	8.80	5.86	2.9341	1.31	6.66	-5.349	1.23	0.096
12000	60	8.66	5.76	2.9014	1.34	6.59	-5.247	1.18	0.098
12400	62	8.54	5.67	2.8706	1.37	6.52	-5.147	1.13	0.100
12800	64	8.42	5.58	2.8415	1.40	6.45	-5.050	1.08	0.102
13200	66	8.31	5.50	2.8139	1.43	6.38	-4.954	1.04	0.104
13600	68	8.20	5.41	2.7877	1.46	6.32	-4.861	1.00	0.106
14000	70	8.10	5.34	2.7628	1.49	6.26	-4.769	0.96	0.108
14400	72	8.00	5.26	2.7392	1.52	6.19	-4.680	0.92	0.110
14800	74	7.91	5.19	2.7167	1.54	6.14	-4.592	0.89	0.113
15200	76	7.82	5.12	2.6953	1.57	6.08	-4.505	0.86	0.115
15600	78	7.73	5.05	2.6749	1.60	6.02	-4.421	0.83	0.117
16000	80	7.65	4.99	2.6554	1.63	5.97	-4.337	0.80	0.119
16400	82	7.57	4.93	2.6368	1.66	5.92	-4.256	0.77	0.121
16800	84	7.49	4.87	2.6189	1.69	5.87	-4.175	0.74	0.123
17200	86	7.42	4.81	2.6019	1.72	5.82	-4.096	0.72	0.125
17600	88	7.34	4.76	2.5855	1.75	5.77	-4.018	0.69	0.128
18000	90	7.28	4.71	2.5698	1.78	5.72	-3.941	0.67	0.130
18400	92	7.21	4.65	2.5548	1.81	5.67	-3.866	0.65	0.132
18800	94	7.14	4.60	2.5404	1.84	5.63	-3.792	0.63	0.134
19200	96	7.08	4.56	2.5265	1.87	5.58	-3.718	0.61	0.136
19600	98	7.02	4.51	2.5132	1.89	5.54	-3.646	0.59	0.138
20000	100	6.96	4.46	2.5003	1.92	5.50	-3.575	0.57	0.140
20400	102	6.91	4.42	2.4880	1.95	5.46	-3.504	0.56	0.142
20800	104	6.85	4.38	2.4761	1.98	5.42	-3.435	0.54	0.145
21200	106	6.80	4.34	2.4646	2.01	5.38	-3.366	0.52	0.147
21600	108	6.75	4.30	2.4535	2.04	5.34	-3.298	0.51	0.149
22000	110	6.70	4.26	2.4429	2.07	5.30	-3.231	0.50	0.151
22400	112	6.65	4.22	2.4326	2.10	5.26	-3.165	0.48	0.153
22800	114	6.60	4.18	2.4227	2.13	5.23	-3.100	0.47	0.155
23200	116	6.56	4.15	2.4131	2.16	5.19	-3.035	0.46	0.157
23600	118	6.51	4.11	2.4038	2.19	5.16	-2.971	0.44	0.159
24000	120	6.47	4.08	2.3948	2.22	5.12	-2.908	0.43	0.162
24400	122	6.43	4.04	2.3861	2.24	5.09	-2.846	0.42	0.164
24800	124	6.39	4.01	2.3777	2.27	5.06	-2.784	0.41	0.166
25200	126	6.35	3.98	2.3696	2.30	5.03	-2.722	0.40	0.168
25600	128	6.31	3.95	2.3617	2.33	4.99	-2.662	0.39	0.170
26000	130	6.27	3.92	2.3541	2.36	4.96	-2.602	0.38	0.172
26400	132	6.23	3.89	2.3467	2.39	4.93	-2.542	0.37	0.174
26800	134	6.20	3.86	2.3396	2.42	4.90	-2.483	0.36	0.176
27200	136	6.16	3.83	2.3326	2.45	4.87	-2.425	0.35	0.179
27600	138	6.13	3.80	2.3259	2.48	4.84	-2.367	0.35	0.181
28000	140	6.09	3.77	2.3194	2.51	4.82	-2.309	0.34	0.183
28400	142	6.06	3.75	2.3130	2.54	4.79	-2.252	0.33	0.185
28800	144	6.03	3.72	2.3069	2.57	4.76	-2.196	0.32	0.187
29200	146	6.00	3.69	2.3009	2.59	4.73	-2.140	0.31	0.189
29600	148	5.96	3.67	2.2951	2.62	4.71	-2.084	0.31	0.191
30000	150	5.93	3.65	2.2895	2.65	4.68	-2.029	0.30	0.193
30400	152	5.91	3.62	2.2840	2.68	4.66	-1.974	0.29	0.196

Climber Ascent Speed (km/hr)	200	Time Interval		2	Earth's Mass (kg)	5.974E+24	Earth rotation (Θ/sec)		7.29212E-05
Earth's Mean Radius	6.378E+06	Gravitational Constant		6.674E-11	mμ - Earth	3.987E+14	Sidereal Day (hours)		23.9344696
Altitude (km)	**Time (hrs)**	**ΔV Hyperbolic (km/s)**	**ΔV park (km/s)**	**Δ V Boost Required to reach Mars (km/s)**	**Climber's Horizontal Velocity (km/sec)**	**Earth Escape Velocity (km/sec)**	**Excess Climber Velocity (ΔV Potential) (km/s)**	**Earth's Gravity (m/s^2)**	**Centrifugal Force (m/s^2)**
30800	154	5.88	3.60	2.2787	2.71	4.63	-1.920	0.29	0.198
31200	156	5.85	3.57	2.2735	2.74	4.61	-1.866	0.28	0.200
31600	158	5.82	3.55	2.2685	2.77	4.58	-1.813	0.28	0.202
32000	160	5.79	3.53	2.2636	2.80	4.56	-1.760	0.27	0.204
32400	162	5.77	3.51	2.2589	2.83	4.53	-1.707	0.27	0.206
32800	164	5.74	3.49	2.2543	2.86	4.51	-1.654	0.26	0.208
33200	166	5.71	3.46	2.2498	2.89	4.49	-1.602	0.25	0.210
33600	168	5.69	3.44	2.2454	2.92	4.47	-1.551	0.25	0.213
34000	170	5.67	3.42	2.2411	2.94	4.44	-1.499	0.24	0.215
34400	172	5.64	3.40	2.2370	2.97	4.42	-1.448	0.24	0.217
34800	174	5.62	3.38	2.2329	3.00	4.40	-1.398	0.24	0.219
35200	176	5.59	3.37	2.2290	3.03	4.38	-1.347	0.23	0.221
35600	178	5.57	3.35	2.2252	3.06	4.36	-1.297	0.23	0.223
35786	178.93	5.56	3.34	2.2234	3.07	4.35	-1.274	0.22	0.224
36000	180	5.55	3.33	2.2214	3.09	4.34	-1.247	0.22	0.225
36400	182	5.53	3.31	2.2178	3.12	4.32	-1.198	0.22	0.227
36800	184	5.51	3.29	2.2142	3.15	4.30	-1.149	0.21	0.230
37200	186	5.48	3.27	2.2108	3.18	4.28	-1.100	0.21	0.232
37600	188	5.46	3.26	2.2074	3.21	4.26	-1.051	0.21	0.234
38000	190	5.44	3.24	2.2041	3.24	4.24	-1.003	0.20	0.236
38400	192	5.42	3.22	2.2009	3.27	4.22	-0.955	0.20	0.238
38800	194	5.40	3.21	2.1978	3.29	4.20	-0.907	0.20	0.240
39200	196	5.38	3.19	2.1948	3.32	4.18	-0.859	0.19	0.242
39600	198	5.36	3.17	2.1918	3.35	4.16	-0.812	0.19	0.244
40000	200	5.35	3.16	2.1889	3.38	4.15	-0.765	0.19	0.247
40400	202	5.33	3.14	2.1861	3.41	4.13	-0.718	0.18	0.249
40800	204	5.31	3.13	2.1833	3.44	4.11	-0.671	0.18	0.251
41200	206	5.29	3.11	2.1807	3.47	4.09	-0.624	0.18	0.253
41600	208	5.27	3.10	2.1780	3.50	4.08	-0.578	0.17	0.255
42000	210	5.26	3.08	2.1755	3.53	4.06	-0.532	0.17	0.257
42400	212	5.24	3.07	2.1730	3.56	4.04	-0.486	0.17	0.259
42800	214	5.22	3.05	2.1705	3.59	4.03	-0.441	0.16	0.262
43200	216	5.21	3.04	2.1682	3.62	4.01	-0.395	0.16	0.264
43600	218	5.19	3.02	2.1658	3.64	3.99	-0.350	0.16	0.266
44000	220	5.17	3.01	2.1636	3.67	3.98	-0.305	0.16	0.268
44400	222	5.16	3.00	2.1614	3.70	3.96	-0.260	0.15	0.270
44800	224	5.14	2.98	2.1592	3.73	3.95	-0.215	0.15	0.272
45200	226	5.13	2.97	2.1571	3.76	3.93	-0.171	0.15	0.274
45600	228	5.11	2.96	2.1550	3.79	3.92	-0.126	0.15	0.276
46000	230	5.10	2.94	2.1530	3.82	3.90	-0.082	0.15	0.279
46400	232	5.08	2.93	2.1511	3.85	3.89	-0.038	0.14	0.281
46750	233	5.07	2.92	2.1494	3.87	3.87	0.000	0.14	0.283
46800	234	5.07	2.92	2.1492	3.88	3.87	0.006	0.14	0.283
47200	236	5.05	2.91	2.1473	3.91	3.86	0.049	0.14	0.285
47600	238	5.04	2.89	2.1455	3.94	3.84	0.093	0.14	0.287
48000	240	5.03	2.88	2.1437	3.97	3.83	0.136	0.13	0.289
48400	242	5.01	2.87	2.1419	3.99	3.82	0.179	0.13	0.291
48800	244	5.00	2.86	2.1402	4.02	3.80	0.222	0.13	0.293
49200	246	4.98	2.85	2.1386	4.05	3.79	0.265	0.13	0.296
49600	248	4.97	2.83	2.1369	4.08	3.77	0.308	0.13	0.298
50000	250	4.96	2.82	2.1354	4.11	3.76	0.350	0.13	0.300
50400	252	4.95	2.81	2.1338	4.14	3.75	0.393	0.12	0.302
50800	254	4.93	2.80	2.1323	4.17	3.73	0.435	0.12	0.304
51200	256	4.92	2.79	2.1308	4.20	3.72	0.477	0.12	0.306
51600	258	4.91	2.78	2.1294	4.23	3.71	0.519	0.12	0.308
52000	260	4.90	2.77	2.1280	4.26	3.70	0.561	0.12	0.310
52400	262	4.88	2.76	2.1266	4.29	3.68	0.603	0.12	0.313
52800	264	4.87	2.75	2.1252	4.32	3.67	0.645	0.11	0.315
53200	266	4.86	2.74	2.1239	4.34	3.66	0.686	0.11	0.317
53600	268	4.85	2.73	2.1226	4.37	3.65	0.728	0.11	0.319
54000	270	4.84	2.72	2.1214	4.40	3.63	0.769	0.11	0.321
54400	272	4.83	2.71	2.1202	4.43	3.62	0.810	0.11	0.323
54800	274	4.82	2.70	2.1190	4.46	3.61	0.851	0.11	0.325
55200	276	4.81	2.69	2.1178	4.49	3.60	0.892	0.11	0.327
55600	278	4.79	2.68	2.1167	4.52	3.59	0.933	0.10	0.330
56000	280	4.78	2.67	2.1156	4.55	3.58	0.973	0.10	0.332
56400	282	4.77	2.66	2.1145	4.58	3.56	1.014	0.10	0.334
56800	284	4.76	2.65	2.1134	4.61	3.55	1.054	0.10	0.336
57200	286	4.75	2.64	2.1124	4.64	3.54	1.095	0.10	0.338
57600	288	4.74	2.63	2.1114	4.67	3.53	1.135	0.10	0.340
58000	290	4.73	2.62	2.1104	4.69	3.52	1.175	0.10	0.342
58400	292	4.72	2.61	2.1094	4.72	3.51	1.215	0.10	0.344
58800	294	4.71	2.60	2.1085	4.75	3.50	1.255	0.09	0.347
59200	296	4.70	2.59	2.1075	4.78	3.49	1.295	0.09	0.349
59600	298	4.69	2.59	2.1066	4.81	3.48	1.335	0.09	0.351
60000	300	4.68	2.58	2.1058	4.84	3.47	1.374	0.09	0.353
60400	302	4.67	2.57	2.1049	4.87	3.46	1.414	0.09	0.355
60800	304	4.66	2.56	2.1041	4.90	3.45	1.453	0.09	0.357

Climber Ascent Speed (km/hr)	200		Time Interval	2	Earth's Mass (kg)	5.974E+24		Earth rotation (Θ/sec)	7.29212E-05
Earth's Mean Radius	6.378E+06	Gravitational Constant		6.674E-11	mμ - Earth	3.987E+14		Sidereal Day (hours)	23.9344696
Altitude (km)	Time (hrs)	ΔV Hyperbolic (km/s)	ΔV park (km/s)	Δ V Boost Required to reach Mars (km/s)	Climber's Horizontal Velocity (km/sec)	Earth Escape Velocity (km/sec)	Excess Climber Velocity (ΔV Potential) (km/s)	Earth's Gravity (m/s^2)	Centrifugal Force (m/s^2)
61200	306	4.66	2.55	2.1033	4.93	3.44	1.493	0.09	0.359
61600	308	4.65	2.54	2.1025	4.96	3.42	1.532	0.09	0.361
62000	310	4.64	2.54	2.1017	4.99	3.41	1.571	0.09	0.364
62400	312	4.63	2.53	2.1009	5.02	3.40	1.610	0.08	0.366
62800	314	4.62	2.52	2.1002	5.04	3.40	1.649	0.08	0.368
63200	316	4.61	2.51	2.0995	5.07	3.39	1.688	0.08	0.370
63600	318	4.60	2.50	2.0988	5.10	3.38	1.727	0.08	0.372
64000	320	4.59	2.50	2.0981	5.13	3.37	1.766	0.08	0.374
64400	322	4.59	2.49	2.0974	5.16	3.36	1.805	0.08	0.376
64800	324	4.58	2.48	2.0968	5.19	3.35	1.843	0.08	0.378
65200	326	4.57	2.47	2.0961	5.22	3.34	1.882	0.08	0.381
65600	328	4.56	2.46	2.0955	5.25	3.33	1.920	0.08	0.383
66000	330	4.55	2.46	2.0949	5.28	3.32	1.959	0.08	0.385
66400	332	4.54	2.45	2.0943	5.31	3.31	1.997	0.08	0.387
66800	334	4.54	2.44	2.0938	5.34	3.30	2.035	0.07	0.389
67200	336	4.53	2.44	2.0932	5.37	3.29	2.073	0.07	0.391
67400	335	4.52	2.43	2.0929	5.38	3.29	2.092	0.07	0.392
67600	338	4.52	2.43	2.0927	5.39	3.28	2.111	0.07	0.393
68000	340	4.51	2.42	2.0922	5.42	3.27	2.150	0.07	0.396
68400	342	4.51	2.41	2.0916	5.45	3.27	2.187	0.07	0.398
68800	344	4.50	2.41	2.0911	5.48	3.26	2.225	0.07	0.400
69200	346	4.49	2.40	2.0907	5.51	3.25	2.263	0.07	0.402
69600	348	4.48	2.39	2.0902	5.54	3.24	2.301	0.07	0.404
70000	350	4.48	2.39	2.0897	5.57	3.23	2.338	0.07	0.406
70400	352	4.47	2.38	2.0893	5.60	3.22	2.376	0.07	0.408
70800	354	4.46	2.37	2.0889	5.63	3.21	2.414	0.07	0.410
71200	356	4.45	2.37	2.0884	5.66	3.21	2.451	0.07	0.413
71600	358	4.45	2.36	2.0880	5.69	3.20	2.488	0.07	0.415
72000	360	4.44	2.35	2.0876	5.72	3.19	2.526	0.06	0.417
72400	362	4.43	2.35	2.0872	5.74	3.18	2.563	0.06	0.419
72800	364	4.43	2.34	2.0869	5.77	3.17	2.600	0.06	0.421
73200	366	4.42	2.33	2.0865	5.80	3.17	2.637	0.06	0.423
73600	368	4.41	2.33	2.0862	5.83	3.16	2.675	0.06	0.425
74000	370	4.41	2.32	2.0858	5.86	3.15	2.712	0.06	0.427
74400	372	4.40	2.31	2.0855	5.89	3.14	2.749	0.06	0.430
74800	374	4.39	2.31	2.0852	5.92	3.13	2.785	0.06	0.432
75200	376	4.39	2.30	2.0849	5.95	3.13	2.822	0.06	0.434
75600	378	4.38	2.30	2.0846	5.98	3.12	2.859	0.06	0.436
76000	380	4.37	2.29	2.0843	6.01	3.11	2.896	0.06	0.438
76400	382	4.37	2.28	2.0840	6.04	3.10	2.933	0.06	0.440
76800	384	4.36	2.28	2.0837	6.07	3.10	2.969	0.06	0.442
77200	386	4.36	2.27	2.0835	6.09	3.09	3.006	0.06	0.444
77600	388	4.35	2.27	2.0832	6.12	3.08	3.042	0.06	0.447
78000	390	4.34	2.26	2.0830	6.15	3.07	3.079	0.06	0.449
78400	392	4.34	2.25	2.0827	6.18	3.07	3.115	0.06	0.451
78800	394	4.33	2.25	2.0825	6.21	3.06	3.152	0.05	0.453
79200	396	4.33	2.24	2.0823	6.24	3.05	3.188	0.05	0.455
79600	398	4.32	2.24	2.0821	6.27	3.05	3.224	0.05	0.457
80000	400	4.31	2.23	2.0819	6.30	3.04	3.260	0.05	0.459
80400	402	4.31	2.23	2.0817	6.33	3.03	3.297	0.05	0.461
80800	404	4.30	2.22	2.0815	6.36	3.02	3.333	0.05	0.464
81200	406	4.30	2.22	2.0813	6.39	3.02	3.369	0.05	0.466
81600	408	4.29	2.21	2.0812	6.42	3.01	3.405	0.05	0.468
82000	410	4.29	2.20	2.0810	6.44	3.00	3.441	0.05	0.470
82400	412	4.28	2.20	2.0809	6.47	3.00	3.477	0.05	0.472
82800	414	4.27	2.19	2.0807	6.50	2.99	3.513	0.05	0.474
83200	416	4.27	2.19	2.0806	6.53	2.98	3.549	0.05	0.476
83600	418	4.26	2.18	2.0805	6.56	2.98	3.584	0.05	0.478
84000	420	4.26	2.18	2.0803	6.59	2.97	3.620	0.05	0.481
84400	422	4.25	2.17	2.0802	6.62	2.96	3.656	0.05	0.483
84800	424	4.25	2.17	2.0801	6.65	2.96	3.692	0.05	0.485
85200	426	4.24	2.16	2.0800	6.68	2.95	3.727	0.05	0.487
85600	428	4.24	2.16	2.0799	6.71	2.94	3.763	0.05	0.489
86000	430	4.23	2.15	2.0798	6.74	2.94	3.798	0.05	0.491
86400	432	4.23	2.15	2.0797	6.77	2.93	3.834	0.05	0.493
86800	434	4.22	2.14	2.0797	6.79	2.93	3.869	0.05	0.495
87200	436	4.22	2.14	2.0796	6.82	2.92	3.905	0.05	0.498
87600	438	4.21	2.13	2.0795	6.85	2.91	3.940	0.05	0.500
88000	440	4.21	2.13	2.0795	6.88	2.91	3.975	0.04	0.502
88400	442	4.20	2.12	2.0794	6.91	2.90	4.011	0.04	0.504
88800	444	4.20	2.12	2.0794	6.94	2.89	4.046	0.04	0.506
89200	446	4.19	2.11	2.0793	6.97	2.89	4.081	0.04	0.508
89600	448	4.19	2.11	2.0793	7.00	2.88	4.116	0.04	0.510
90000	450	4.18	2.10	2.0793	7.03	2.88	4.152	0.04	0.512
90400	452	4.18	2.10	2.0792	7.06	2.87	4.187	0.04	0.515
90800	454	4.17	2.10	2.0792	7.09	2.86	4.222	0.04	0.517
91200	456	4.17	2.09	2.0792	7.12	2.86	4.257	0.04	0.519