IAC-04-IAA.3.8.3.01

THE SPACE ELEVATOR AND NASA'S NEW SPACE INITIATIVE

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ABSTRACT

We present a lunar exploration program based on use of a space elevator. This work is directly based on a proposal recently submitted to a NASA Broad Area Announcement for concept development. The concept lays out a plan for construction of a lunar base with a crew of at least eight people and allows for dramatic expansion and development of the rest of the solar system. The cost of exploration program proposed by President Bush (lunar base, manned Mars base and solar system exploration) can be completed for $120B when a space elevator is utilized. For comparison a comparable rocket based program will cost ~$500B. The space elevator program also has greatly reduced risk, increased redundancy, excess launch capacity, likelihood to become self-sufficient and direct application to developing the remainder of the solar system.

The proposed concept study was not selected for funding by NASA. At this time the space elevator is not included in the NASA space exploration program or funded in any form by NASA except through a congressional appropriation ($1.9M to ISR/MSFC). The combination of funding, administration and schedule of the current NASA exploration program appear to preclude implementation of the space elevator. It is also observed that private investment and construction of the space elevator is a more likely development scenario based on current investments and interest.

INTRODUCTION

NASA'S EXPLORATION PROGRAM

On January 14, 2004, President George Bush articulated a new vision for space exploration, "A Renewed Spirit of Discovery." In February, 2004, NASA released "The Vision for Space Exploration," its response to the president's challenge. The key aspects of the new NASA initiative are:

The fundamental goal of this vision is to advance U. S. scientific, security, and economic interest through a robust space exploration program.

> *(1) Implement a sustained and affordable human and robotic program to explore the solar system and beyond.*

(2) Extend human presence across the solar system, starting with a human return to the moon by the year 2020, in preparation for human exploration of Mars and other destinations.

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

This is an ambitious set of goals. The U.S. has tried similar sets of goals before (1970s, 1989) and failed. The Apollo program lost public interest and support after the stated goals were achieved. In the late sixties, 40% of the adult population of the United States supported the Apollo program. The Space Exploration Initiative in 1989 (NASA's *90-Day Study of the Exploration of the Moon and Mars*, 1989) was proposed but not approved by congress six months after initiation due to the cost – an estimated $500 billion. The Space Exploration Initiative was similar in scope to the exploration program proposed this year with manned activities on the moon and Mars.

A WORKABLE SPACE EXPLORATION PROGRAM

We will assume that the constraints placed on the prior NASA exploration programs still exist: 1) it must be valuable or of interest to the public and 2) it must have a total cost of much less than $500 billion dollars.

Since the Apollo program failed to convert into a long-term, self-sustaining program, we can assume that placing a couple people on the moon or even Mars for a few days a year is not sufficient. For a program of 20 years in duration we can probably assume that the program must do much more than Apollo which was a 10-year program 40 years ago. This may be a permanent manned base with valuable activities such as manufacturing or scientific studies. Due to safety considerations this means a base with a minimum crew of four people but more likely eight. This is the lower limit of what can be done in a federally-funded exploration program. When thinking about a publicly-supported, federally-funded space exploration program of this extent it must have a support base larger than Apollo (40% of the adult population).

The funding limits define the upper end of what can be considered for an exploration program. To transport a crew of eight to the moon, rotate them out each six months and keep them supplied will require 150 tons to be delivered to the lunar surface per year or 8 heavy lift vehicles with the performance of at least a Saturn V. The habitat for this crew will require 500 tons and need about 20% replacement each year. This is 25 additional heavy-lift vehicles initially and five more each year. If we run this lunar base for 10 years we find that it would require 155 launches. A reasonable estimate is that these heavy-lift vehicles, reusable or expendable, would cost $1 billion per launch since these vehicles are not yet developed and require higher performance than the $500 million per launch Space Shuttle. We will also not realize much cost savings due to multiple launches because we are talking about 15 launches per year which is not dramatically more than seen by the current shuttle. The launch costs of this effort then appear to be around $155 billion not including any development costs for the heavy lift vehicle.

Funding is also required for development and construction of the hardware used on the lunar surface. Estimates for this hardware vary but can run from $50 billion up to $100 billion. The total cost then comes in at $20 billion to $25 billion average per year for ten years – higher than the current $15 billion NASA budget. It should be considered that the current NASA budget funds NASA centers and diverse programs and can not be redirected to paying for launch vehicles or much of the exploration initiative without politically-nonviable lay-offs of thousands of individuals. In reality, NASA has a few billion dollars each year that can effectively be directed at the exploration program.

If we include efforts to go to Mars or to send robotic missions to explore the cost will increase dramatically. Considering two robotic missions a year and placing humans on the Martian surface to stay we find a funding profile equal to or larger than what we found above for the lunar base. This will place the total cost of a rocket-based exploration program at approximately $500B. This is not much of a surprise since a similar program proposed in 1989 had the same funding requirement. With the realistic political fluctuations and other demands on the federal budget that occur over any 20-year time span, it is likely that this program will be cut or marginalized in a similar fashion to the 1989 program. To define a successful program we need to have a much more valuable concept that costs less.

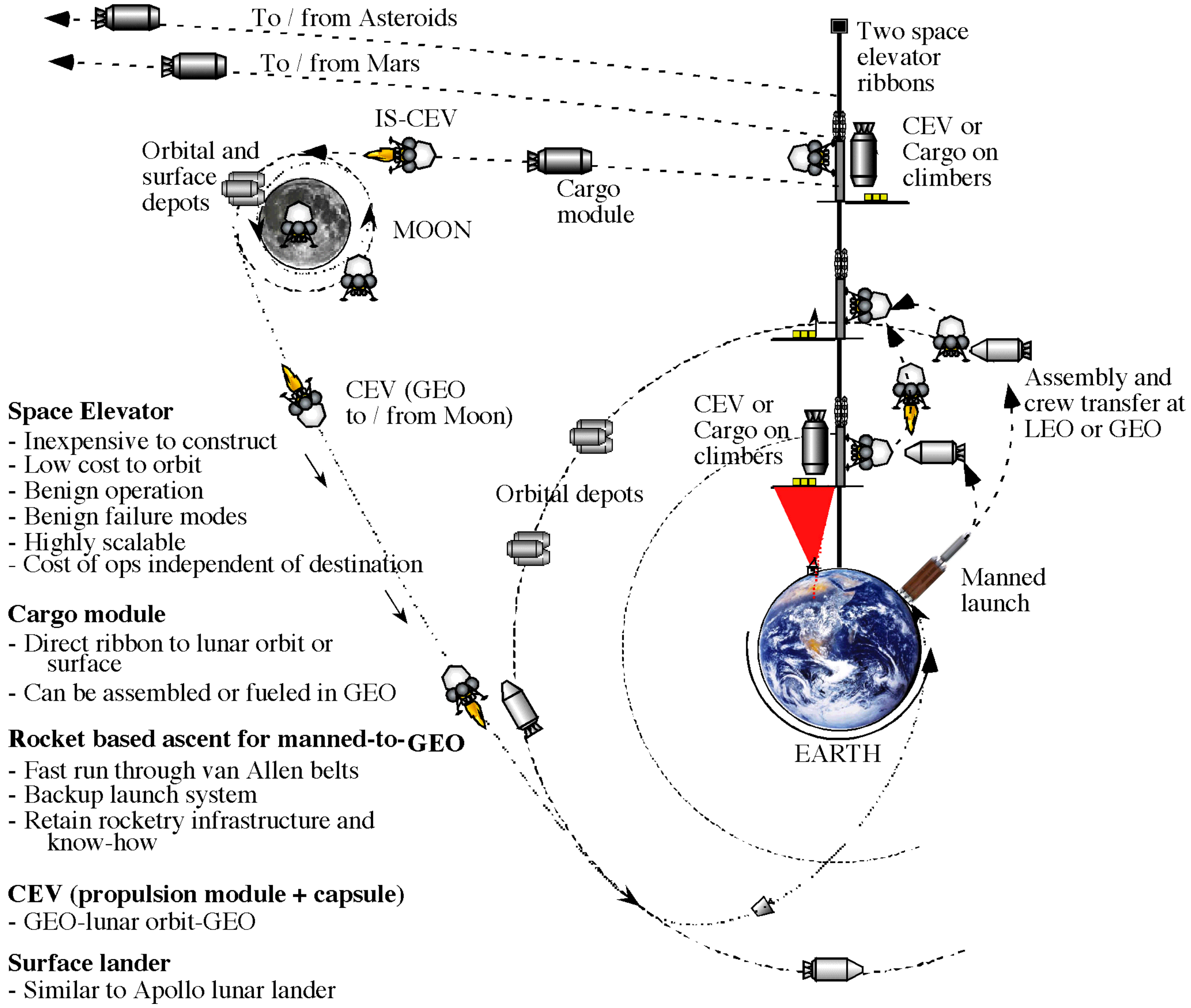

Figure 1: Overview of the proposed exploration program.

THE SPACE ELEVATOR IN NASA'S EXPLORATION PROGRAM

One lunar exploration concept recently proposed to NASA is based on an innovative transport system (*The Space Elevator*, Edwards and Westling, 2003) and well-studied modular or prefab lunar base structure designs, modified to take advantage of the space elevator's capabilities. This unique program has a number of benefits, as we will discuss. The proposing team consisted of: the author, Dr. Paul Spudis (John Hopkins), Dr. Heinz-Hermann Koelle (Berlin Technical University), Dr. Michael Duke (Colorado School of Mines), Ms. Pamela Luskin (Futron), Ms. Patricia Russell (X Tech), Dr. Hyam Benaroya (Rutgers University), Dr. David Raitt (European Space Agency), Mr. Ben Shelef (Spaceward), and Dr. Bryan Laubscher (Los Alamos National Laboratory).

In the proposed concept the space elevator is utilized for delivery of cargo from Earth to L1, the lunar surface or lunar parking orbit, and delivery of Crew Exploration Vehicles (CEVs) from geosynchronous orbit (GEO) to L1, lunar orbit or the lunar surface. A medium-lift launcher delivers a crewed capsule to Low-Earth Orbit (LEO) or GEO, where it is docked with a reusable space-resident Earth-moon propulsion module (see figure 1).

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

By providing supplies and safe havens at various locations (LEO, GEO, L1, lunar orbit, lunar surface) and constructing CEVs that can reach multiple destinations we have used the launch capacity of the elevator to gain operational flexibility and thus safety. These depots can be modular and low-tech thus establishing them will be inexpensive compared to the permanently crewed habitats.

With this new set of working parameters, options become available in large-volume rigid structures for habitats (spheres, boxes, or cylinders over 10m in dimension), or mass-produced modular units that may be more massive or replicated easily, inexpensively, and safely with large risk margins. Examples of such can be found in terrestrial commercial applications (liquid storage tanks). In the life-support system we find that large-volume biological life support system enclosures may be viable as are the closed cycle life support systems that require large initial mass but provide better long-term affordability.

TRANSPORT SYSTEM DESCRIPTION

Earth-to-space transportation has always been a major stumbling block. In our proposed scenario we utilize the space elevator to give us the capabilities required to meet the program objectives. The entire transportation system consists of two space elevators, Earth-to-space and in-space CEVs, and cargo modules. A space elevator-based transportation concept offers the following advantages:

- Low launch costs
- Relatively simple and inexpensive construction and operation
- Benign operation environment (no launch forces, no fairing to limit volume)
- Benign failure modes
- Scalable
- Cost and operations are largely the same for the space elevator independent of destination
- Excess launch capacity that can be utilized for other space programs or sold

UTILIZING THE SPACE ELEVATOR

The baseline space elevator system considered in the proposed concept consists of:

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

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

Crew: In the current space elevator design, travel time from Earth-to-GEO is 8 days. Due to this length of time we will examine crew transport on the elevator but baseline crew transport on conventional rockets. This will require human-rating a medium-lift rocket capable of carrying a transport CEV to LEO or GEO. From LEO an in-space CEV delivered and fueled by the elevator can transport crew members to GEO. Once at GEO, crews will board in-space CEVs to be carried up the elevator to the translunar trajectory release point where the elevator's velocity places them on course for a specified destination, no propellant needed.

CEV

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

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

LUNAR PARKING ORBIT

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

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

SAFETY

The fact that the operations are to be long-duration and ongoing means that mishaps will eventually happen. How mishaps are dealt with is critical.

The key to recovering from unexpected situations is flexibility, and flexibility stems directly from capabilities. In many cases the requirement for mission flexibility will conflict with design simplicity or mass limits. An integrated all-in-one system may appear more robust in the short-term but fall short in the long-term of a more staged, modular, flexible system.

The large mass capacity of the elevator will allow crewed components to be over-designed, and carry ample propellant surpluses, allowing for greater mission flexibility, recoverabity, and ultimately, sustainability. In our proposed effort, redundant fuel, supplies, habitats, rovers, parts and CEVs can be placed in geosynchronous orbit (100 metric tons: four T-CEVs, habitat and provisions for eight people for two months) and lunar orbits (200 metric tons: four T-CEVs, two IS-CEVs, habitat and provisions for 16 people for two months) and on the lunar surface (300 metric tons: five IS-CEVs, eight rovers, five outposts, supplies for 16 people for two months) to provide multiple back-ups for the exploration endeavors.

RELIABILITY

Failure modes for the space elevator can relate to climbers, the ribbon or the power system.

Inherently climber failures are not catastrophic. During construction, 280 climbers will ascend the elevator to establish operations and reliability. The default scenario for a malfunctioning climber is to stop. A second climber can be used as a tug to take the malfunctioning climber to the required destination.

Severed ribbons will have programmatic repercussions (financial and public relations) though the ribbons will be designed to minimize this possibility and any ribbon that does fall will burn up on re-entry causing no substantial damage. The current system is designed to have a lifetime of hundreds of years. A second redundant ribbon is also proposed such that a severed ribbon can be replaced on a 6-month to one-year timeframe at a cost of several hundred million dollars. In our scenario a single space elevator is sufficient to conduct the exploration program.

Misaligned lasers will have few detrimental effects. Loss of power stops the ascent of a climber but once power is restored the climber will begin its ascent again. The power density is at an eye-safe level.

Reliability of the CEVs rest on their general integrity and propulsion systems. The reliability of mature, operational systems has been established.

AFFORDABILITY

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

For delivery there is a $20B capital expense and $1B/year operating costs for two space elevators that will be able to lift 3000 tons per year from Earth and throw it directly to the moon. This capacity is more than sufficient for any of lunar models we examined. However, we will investigate the possibility of a commercial component of the exploration program that would allow NASA to reduce its expenditures by using the excess launch capacity for revenue generation. The CEVs are expected to cost a total of $2.5B for development and production of eight IS-CEVs and $2B for development and production of eight T-CEVs. The cargo modules are expected to run $1B for eight.

Total program expenditures are estimated to be $68B primarily spent between 2005 and 2023. The funding outlays for the “outpost” scenario can be scheduled such that the total, system and delivery, annual expenses will ramp up to a peak of $5B in the year 2020 and then taper down to less than $2B per year. As much as $2B per year may be recoverable through sale of the excess launch capacity (conducted by a private enterprise possibly on a lease program). In 2019, the first human will be safely on the moon. By 2022, a permanent human outpost on the lunar surface will be established and the next stage, a “laboratory” level lunar program with a population of 80, can be initiated. If we can establish the support we believe possible with our proposed program then expanding to the next level should be straight forward.

Modification to the lunar base due to implementation of the space elevator will further reduce the base construction costs due to simplified engineering and improve safety margins by allowing for more redundancy and back-up systems.

SUSTAINABILITY

Sustainability is achieved by reducing the external desire to cut the program (reduce the costs, reduce the frequency of negative events) and increasing the desire to maintain the program (increase the program's value and backing from the public, corporations, military and international allies).

Implementing the space elevator reduces launch and program costs as we discuss above. With the 95% decrease in launch price expected in this program, the commercial space market would be expected to increase by 125% in 2020 (Futron ASCENT Market Share Model). The launch revenue from this increase alone would be sufficient to sustain a space elevator infrastructure. Once built, the transportation infrastructure would be self-sustaining and expand rapidly. Commercial developments at LEO and GEO are likely to grow and could provide support, logistical and political, for the exploration program.

A greater threat to sustainability comes from a program failure (loss of life, loss of valued objectives). Implementing the space elevator will increase program safety and performance thus preventing loss of life and creating a more valuable program.

EXTENSIBILITY/EVOLVABILITY

The scenario we are proposing is adaptable to exploration of Mars and asteroids. Modular units with similar construction to the IS-CEVs can be produced and joined to form larger living units (~200m^3) for longer duration stays. These larger modules can be released onto a trajectory with the elevator to Mars and near-Earth asteroids. Since the Earth elevator is equatorial, a plane change engine may be required depending on the launch window.

No additional infrastructure needs to be built and the elevator operations are already factored into the discussion above. Thus a Martian base could realistically cost a similar amount to the lunar base above, ~$40B. Additionally, we can consider launching multiple robotic missions each year and need only account for the program costs since launch costs are paid for. Thus the entire program proposed by President Bush and NASA could be done for ~$120B compared to the $500B as a baseline for a rocket-based scenario – an 75% reduction in cost.

In the long-term our proposed scenario opens the rest of the solar system. Elevators on the Moon, asteroids, and Mars have been examined and found to be viable. These elevators can be assembled in Earth orbit and thrown to the destination of application. An elevator on Mars would allow for high-capacity transport to and from the red planet. An asteroid elevator allows for mining and delivery of material to other locations. Asteroid elevators could also serve for trajectory change / velocity boosts to the outer planets.

RISK ASSESSMENT

Utilizing the space elevator as part of the exploration program eliminates some risks and introduces others. Looking at the major subsystems of the space elevator we find that the TRLs (defined in Mankins, J.C., 1995, White Paper, Office of Space Access and Technology, NASA) for the subsystem components and the entire subsystems range from 2-3 up to 9.

Subsystem	TRL
Ribbon	2-3
Lunar base	5-7
Climber	5-9
Anchor	6-9
Spacecraft	6-9
Power beaming	6-9
IS-CEV	7-9
T-CEV	7-9
Cargo Module	7-9
Tracking	8-9

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

The space elevator-related development risk of greatest concern is the high-strength material.

Carbon nanotube materials are maturing rapidly due to commercial interest and with a modest investment can be produced at the strengths required and implemented in a ribbon within two years. The remaining technologies are nearing maturity and will be ready for use in the near future. Our estimates show that development and construction can be completed in 10 years following two years of R&D and we have allowed an additional 3 years for delays. The space elevator can be operational by 2019.

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

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

When considering the entire program we must also consider the risk of achieving the objectives. Utilizing two space elevators in the exploration program we have the capacity to launch 3000 tons to the moon each year for a total operating cost of roughly $1B. This capacity will allow for expeditions of larger and more crews if desired and considerably more hardware and autonomous systems. Comparable launch capacity based on rockets would cost approximately $100B per year (150 heavy-lift vehicles delivering 20 tons to the moon for $600M each).

We believe the greatest operational risk lies in the long range habitation of the moon-base itself. The conditions are unforgiving, and the operations performed are wide-ranging, often dangerous, and on-going. Accidents will happen. For this reason we are instituting multiple emergency options including dispersed independent habitats and stations, fuel, supplies, CEVs and vehicles.

By changing the critical Earth-to-space segment of the transportation system we have a dramatic departure from previous scenarios. Launch costs, designing components to survive the rocket launch environment and capacity are no longer the major concerns. Mass can be traded for higher safety, lower design costs, and expanded performance. The change in the transportation system also brings new risk factors and requires a new risk analysis and mitigation approach. The new risks introduced come in the form of technical (development of the high-strength materials, engineering designs) and non-technical (legal, regulatory, environmental) and integration (CEVs need to be designed for use on the elevator, large structures launched without disassembly or compression). However, the risks that are eliminated include: development of high-performance rockets and CEVs, design risks associated with building components for rocket launch, catastrophic launch failure, and limited redundancy due to funding and mass limitations.

NASA'S RESPONSE TO THIS PROGRAM

NASA's Institute for Advanced Research funded the initial design studies conducted between May 2000 and February 2003 at a level of $570,000. This funding was instrumental in moving the space elevator out of the realm of science fiction and began the serious consideration of a viable design.

On a dozen occasions, the author has briefed NASA Headquarters (Exploration Systems, Space Architect), Langley Research Center, and Marshall Space Flight Center on the space elevator concept. No funding opportunities have been available from NASA for continued research on the space elevator. Due to topic specifications, the space elevator has not been allowed in the space tethers program or propulsion program calls. Some programs have been available for incremental funding of subcomponents (space tethers and SBIRs for high strength materials and lasers). A congressional appropriation directed through NASA at the level of $1.9 million has been secured for work on the space elevator at the Institute for Scientific Research and Marshall Space Flight Center. This appropriation for fiscal year 2004 arrived at the Institute for Scientific Research in mid-August 2004.

The space elevator based exploration program presented here was proposed to NASA's Broad Area Announcement for a $2 million exploration concept study. The proposing team consisted of: the author, Dr. Paul Spudis (John Hopkins), Dr. Heinz-Hermann Koelle (Berlin Technical University), Dr. Michael Duke (Colorado School of Mines), Ms. Pamela Luskin (Futron), Ms. Patricia Russell (X Tech), Dr. Hyam Benaroya (Rutgers University), Dr. David Raitt (European Space Agency), Mr. Ben Shelef (Spaceward), and Dr. Bryan Laubscher (Los Alamos National Laboratory). The proposal was to quantify a space-elevator-based exploration program, conduct a complete risk and system analysis and outline where development work was required. The proposal was not selected for funding. Details on the proposal review have been requested but not yet received and the proposals that were selected have not been announced.

The funding levels offered through the recent NASA Broad Area Announcements for concept studies and technology development range from $2 million for concept studies to a maximum of $40 million for feasibility tests. These funds are distributed over two to four years. These funds are insufficient to develop the space elevator to TRL level 6 required by NASA for acceptance of a new technology for implementation. To meet the timeframe defined by NASA for placing men on the moon, the space elevator will need to be at TRL level 6 by 2007 at the latest. Due to these limits the space elevator can not be realistically considered for implementation in the NASA program.

In conducting this effort, and earlier return on investment studies, we have found that the business potential for the space elevator is sufficient and the development risk at a low enough level now to warrant pursuit of private funding. Private funding, expected in September 2004, for specific components related to the space elevator is greater than the funding in all, but the largest, of the NASA opportunities. Private investors have stated a definitive interest in constructing and utilizing the space elevator.

CONCLUSIONS

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

At this time the space elevator is not included in the NASA space exploration program or funded in any form by NASA except through a congressional appropriation ($1.9M to ISR/MSFC). The combination of funding, administration and schedule of the current NASA exploration program appear to preclude implementation of the space elevator. It is also observed that private investment and construction of the space elevator is a more likely development scenario based on current investments and interest.

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