UNCONVENTIONAL SPACELIFT

Introduction

In late February 1994, Lt Gen Jay W. Kelley, Air University (AU) Commander and Chairman of the SPACECAST 2020 study, asked the faculty of the Graduate School of Engineering at the Air Force Institute of Technology (AFIT) to investigate unconventional approaches to solving our national spacelift problems (attachment). This AFIT study, designed to complement the conventional spacelift study conducted by one of the SPACECAST 2020 teams at AU, was chartered to find ways to launch payloads from the Earth's surface to low-earth orbit without the use of conventional chemical combustion (fuel and oxidizer).

Selected faculty from the Departments of Aeronautics and Astronautics, Electrical and Computer Engineering, Engineering Physics, and Operational Sciences and the SPACECAST 2020 Technology Team worked together to collect and evaluate over two hundred separate references, consisting of more than 3,500 pages of text and covering almost one hundred different unconventional launch techniques. The vast majority of these reference materials were input to a content-retrieval-based document imaging system, provided by Excalibur Technologies Corporation, greatly facilitating the effort. Techniques were evaluated for engineering and scientific feasibility. Those techniques deemed to violate physical principles were quickly discarded from further consideration.

Technical Considerations

Several factors determine the feasibility of any technical solution. The first factor is Newton's Third Law: For every action there is an equal and opposite reaction. To achieve orbital velocity, sufficient momentum must be provided to the payload and the launch vehicle. To do this, typical propulsion systems must either expel a lot of mass at low velocity or a small amount of mass at high velocity. That is, the thrust (rate of change in momentum) needed, F, equals the product of the mass flow rate, dm/dt, and the exit velocity of the fuel, v_e, or

$$F = \frac{dm}{dt} v_e.$$

The thrust, accumulated over time, provides the needed momentum.

A primary figure of merit for any propulsion system is the specific impulse, I_{sp}, which is measured as the impulse (change in momentum) provided per unit weight of fuel expended. The specific impulse, for conventional combustion systems, is proportional to the square root of the combustion chamber temperature over the molecular weight of the fuel. That is,

$$I_{sp} \propto \sqrt{\frac{T_c}{MW}}$$

where T_C is the combustion chamber temperature and *MW* is the molecular weight of the fuel. The propulsion system is most efficient (has the highest specific impulse) when the chamber temperature is high and the molecular weight of the fuel is low. In any real system, the chamber temperature will be limited by the material properties of the combustion chamber. For high-thrust systems, hydrogen is the best fuel since it has the lowest molecular weight.

Methodology

Of the one hundred different launch techniques examined, most were eliminated because they failed to pass one of the following two tests:

- Although their specific impulse was great, their thrust-to-weight ratio was not sufficient to launch from the Earth's surface to low-earth orbit. To permit Earth-to-orbit access, a propulsion system must provide greater than a 1:1 thrust-to-weight ratio. While many of these systems hold promise for an on-orbit transfer vehicle, they do not solve the basic problem of launching to low-earth orbit. Figure 1 shows that of the potential technologies available, only chemical propellants and nuclear fission[1] provide sufficient thrust to merit further consideration.

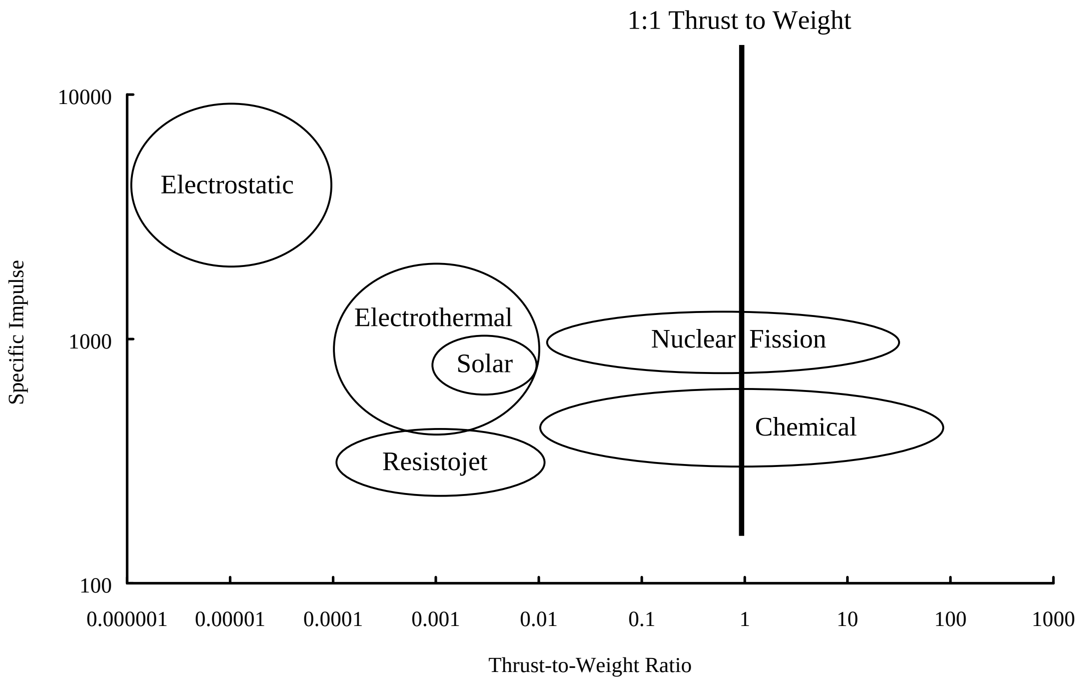

Figure 1. Specific Impulse versus Thrust-to-Weight Ratio[2]

- While theoretically possible, some approaches were not operationally feasible. These included systems such as laser propulsion requiring huge external power sources (on the order of a billion watts) and would have extreme difficulty with atmospheric propagation of the required directed energy.

These constraints narrowed the list of concepts to high-energy-density fuels, antimatter, nuclear, and tethers. These concepts are discussed below.

High-Energy-Density Fuels[3]

The High-Energy-Density Materials (HEDM) Program is a research and development effort managed jointly by the Air Force Phillips Laboratory and the Air Force Office of Scientific Research. The HEDM program represents a collection of concepts to increase energy content in chemical bonds of non-nuclear materials. The fundamental premise for all chemical propulsion is that weakly bound atomic structures rearrange into very strongly bound atomic structures with the release of energy. Strongly bound chemical materials are very well known. Therefore, HEDM investigators are searching for high-energy metastable materials which release much more energy than liquid hydrogen/liquid oxygen combustion, yet are sufficiently stable to be practical propellants. One generally expects high energy release to correlate with instability. The HEDM program explores for candidate materials which are exceptions to this trend. Practical HEDM propulsion systems will require that the chemical reaction products serve as propulsion exhaust. So, to achieve high specific impulse, atoms in candidate metastable structures must be light atoms which produce light product molecules, preferably diatomic molecules. Since the chemical reaction products are exhausted, they must be environmentally benign.

It is important to point out here that improvements in payload to orbit do not track linearly with improvements in specific impulse. For example, at an I_{sp} of 450 seconds, a ten-percent improvement in specific impulse would produce a twenty-percent improvement in payload to orbit. This relationship is illustrated in figure 2.

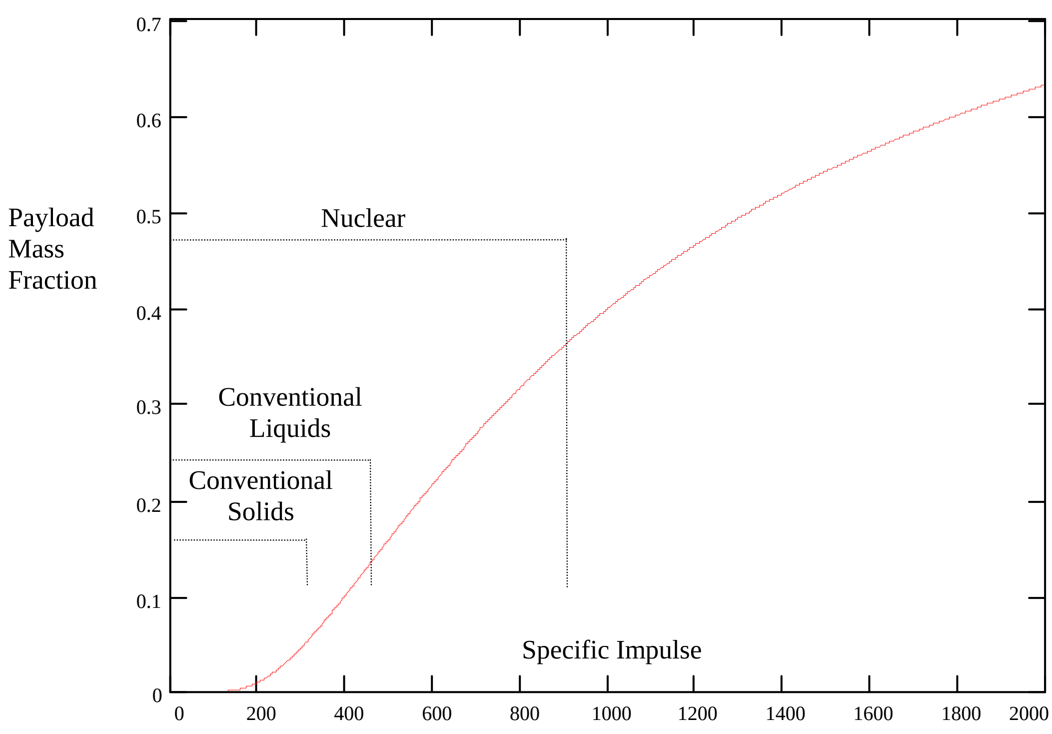

Figure 2. Payload Mass Fraction versus Specific Impulse[4]

The most promising near-term HEDM candidates are evolutionary improvements to the liquid hydrogen/oxygen propellant. These new propellants are based on additives to solid hydrogen and solid oxygen. For example, five percent addition of lithium boride (LiB) to solid hydrogen is projected to produce a 107-second improvement in specific impulse. Addition of fifty percent ozone in a solid oxygen matrix is projected to improve the specific impulse by 25 seconds.

The HEDM program also has a revolutionary component. Revolutionary HEDM candidates are metastable monopropellants which might be decomposed yielding large amounts of energy. Calculations of molecular stability are being used to predict candidate metastable atomic arrangements expected to have very high energy content and practical lifetimes. For example, calculations by University of Georgia scientists suggest that dodecahedral nitrogen (N_{20}) may be metastable. A propulsion system based on the decomposition of N_{20} to diatomic nitrogen (N_2) could provide a specific impulse of about 500 seconds. Metallic molecular hydrogen is another proposed candidate. Experiments are being conducted to identify new high-pressure phases of hydrogen in hope of generating a hydrogen phase which might be metastable at lower pressures. A specific impulse of 1800 seconds for decomposition of metallic hydrogen represents the maximum theoretical specific impulse that can be achieved by chemical means.

The scientific challenges for HEDM are substantial. Candidate HEDM propellants have been proposed based on calculations of stability for novel atomic arrangements. Synthesis of even small amounts of these materials involves large scientific challenges. The probability of identifying a practical HEDM material by any experimental approach is highly uncertain. Until a promising HEDM candidate is identified through the use of computational techniques, the engineering challenges for producing the propellant in quantity or engineering a propulsion system to employ it are largely unknown.

Antimatter Propulsion[5]

Early in the HEDM program it was suggested that the enormous energy released from matter-antimatter annihilation might be useful for propulsion. In a simple picture, antiprotons and positrons would be slowed, trapped, and recombined to form a charged anti-hydrogen cluster. This antimatter cluster forms one part of a bipropellant fuel, the other being ordinary hydrogen. The antimatter cluster is then reacted with ordinary hydrogen and almost completely converted into energy.

The energy density of a propellant is linked to the characteristics of the reaction producing the energy release. Chemical reactions swap bond energies, with the energy released being of the order of electron volts per reaction.[6] Nuclear reactions swap nuclear bond energies releasing energies of the order of millions of electron volts per reaction.[7] Similar to nuclear reactions, antimatter reactions swap rest mass energies, releasing energies of the order of a billion electron volts per reaction.[8]

The concept, in essence, is beautifully simple yet implementation eludes our current understanding and capabilities when we consider the requirements facing any high-energy-density fuel. Any HED fuel must be able to be economically produced in quantity, stored, reacted in a controlled manner, and permit efficient utilization of the energy released to directly or indirectly produce thrust. Antimatter fails each of these requirements. While very small amounts of antimatter would be required to provide the necessary heat source, current methods of producing and storing antiprotons provide trillions of times (12 orders of magnitude) less capability than what is needed.[9]

Even assuming that the host of difficulties associated with production and storage are surmountable, one faces the fundamental problem that the reactions themselves are extremely complex, and the products of the reaction include both high-energy radiation and elementary particles. These products are not terribly useful for propulsion since they are not easily converted to thrust (they are moving very fast and pass right through all but the heaviest materials without depositing their energy).

The environmental and safety concerns are similar to those associated with nuclear propulsion. Even if adequate shielding against the gamma radiation can be provided, temperatures will likely be so high as to require magnetic confinement to prevent meltdown of the reaction chamber.[10] From an operational standpoint, the failure of such a containment system will be catastrophic, resulting in a meltdown of the reactor and release of extremely radioactive by-products. Presently, there does not appear to be any way to make such a magnetic confinement system fail-safe. Therefore, antimatter propulsion systems and fusion reactors, which will also require magnetic confinement systems, were dropped from further consideration.

Nuclear Propulsion[11]

There are a variety of approaches to applying nuclear energy for space propulsion. In nuclear thermal propulsion, a propellant gas is heated as it flows through the core of a nuclear reactor and is then expanded and expelled through a rocket nozzle (see figure 3). The reactor core can be a solid (e.g., uranium carbide particles in a graphite matrix or uranium nitride in a ceramic matrix), liquid, or a gas/plasma. The last two approaches can produce much higher propellant temperatures, resulting in higher specific impulse and greater rocket efficiency. Unfortunately, they are also significantly more challenging to realize since it is extremely difficult to flow a fuel through these reactors without expelling fissionable material in the exhaust. Therefore, this discussion will center on solid-core nuclear thermal propulsion.

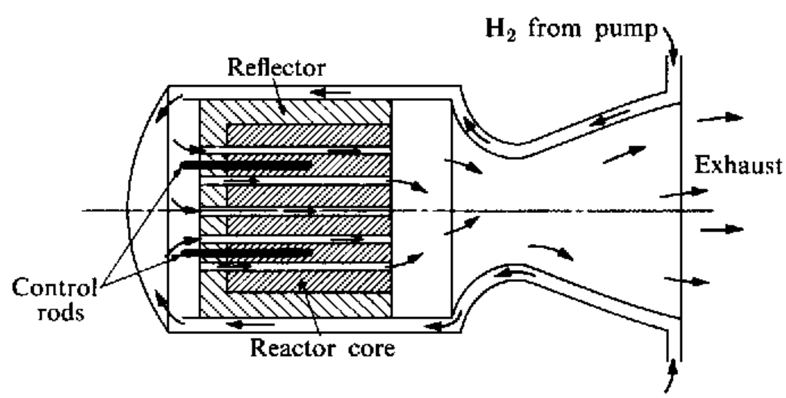

Figure 3. Solid-Core Nuclear Thermal Rocket Engine[12]

Project Rover started in 1955 at Los Alamos National Laboratory, with the goal of developing a solid-core nuclear thermal propulsion rocket using liquid hydrogen as both nozzle coolant and propellant. By 1967, a variety of systems had been developed and tested. The largest provided 200,000 pounds of thrust and was operated at full power for 12 minutes with a reactor system mass of 9,500 kg. Another design produced a specific impulse of 845 seconds.[13] While the program was deemed a technical success, changing national priorities resulted in cancellation of the program in 1973.

Solid-core nuclear thermal rockets have shown considerable technical promise. They can readily achieve specific impulses of 750 to 800 seconds and recent studies have suggested 875 to 900 seconds as goals. Dual-use designs have been proposed which will provide significant electric power from the reactor after the propulsion phase is complete. Furthermore, the proposed technology does not require advances in basic scientific knowledge.

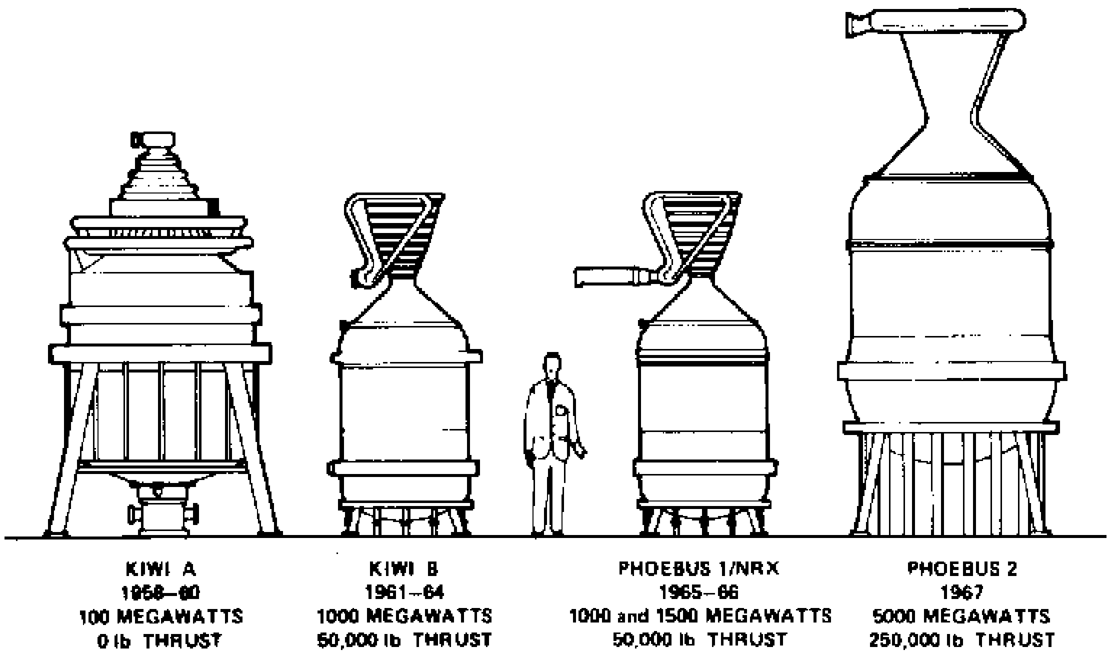

Figure 4. Project Rover Nuclear Rocket Engines[14]

However, some engineering problems nee to be overcome. The 1960s designs envisioned a nuclear rocket engine to be first powered up in Earth orbit for a planetary mission. They were not designed to launch payloads from the Earth's surface, but to operate in the vacuum of Earth orbit. Therefore, some design changes would be necessary. In particular, additional shielding will be required to block radiation emitted to the sides from backscattering off the atmosphere and into the payload. In addition, the Project Rover reactors suffered from fuel erosion in the core, due to the high-speed flow of hot hydrogen gas. Thus, the exhaust contained some uranium and fission products. Reduced fuel erosion can be obtained by using improved materials, thicker cladding, lower hydrogen temperatures, or a larger flow area (to reduce flow velocities). It should be noted that reducing or eliminating fuel erosion is necessary not to make the systems work, but to reduce or eliminate external contamination.

Uncontrolled reentry or launch failures will result in nuclear materials entering the environment, either intact, in pieces, or dispersed as fine particles. Placed in the context of other nuclear hazards, however, it will take thousands of launch failures to put as much fission product activity into the ocean as one sunken submarine reactor. It will take hundreds of launch failures to put as much fission product activity into the atmosphere during an uncontrolled reentry as one of the smallest atmospheric nuclear tests.

Space nuclear propulsion could provide substantial advantages over conventional rocket propulsion. The technical risks are low and much of the work needed has already been done. The remaining problems are technical in nature; no scientific breakthroughs are required (the US does have experience with maintaining operational reactors by military personnel in its nuclear submarine fleet). Overall, the authentic environmental risks are modest. However, the problem very likely will be public acceptance. In a normal launch, a nuclear propulsion system will exhaust detectable, but not dangerous, radiation. In a launch accident, nuclear fuel and some fission products will be dispersed into the lower atmosphere as detectable, but not dangerous, particulates. To a society still regarding the detectable, but not dangerous, emissions from the Three-Mile Island accident as a 'disaster,' such emissions will likely be unacceptable.

Tethers

The most unusual concept examined was that of tethers.[15] Basically just a cable to space, an ideal design might be to run a cable through geostationary orbit all the way to the ground. With the center of mass of the tether orbiting with the same period as the rotation of the earth, it would sit stationary, much like the beanstalk in the fairy tale "Jack and the Beanstalk."

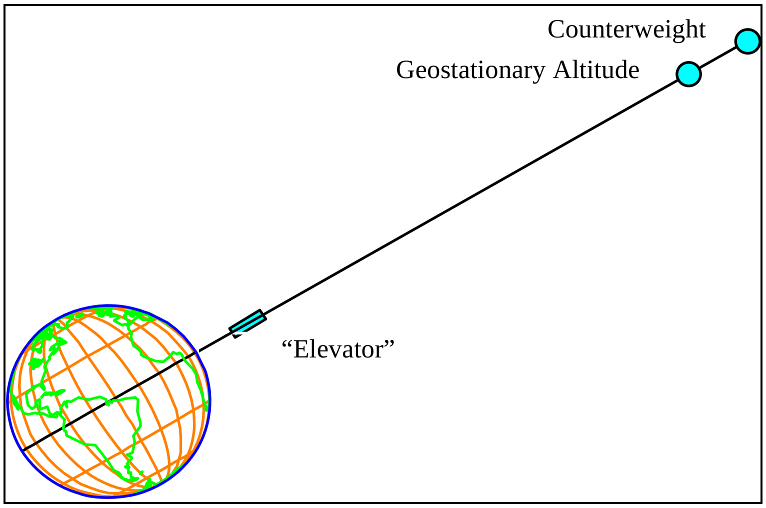

Figure 5. Geostationary Orbiting Tether “Elevator”

However, when examining current tensile strengths and densities of materials to construct such a tether, the mass required for such a project is on the order of a *trillion* kilograms--far exceeding our current manufacturing and spacelift capabilities. When examining the maximum possible tensile strengths theoretically achievable, the literature suggests that less than an order of magnitude improvement is possible in the strength-to-weight ratio of existing materials.

However, another design seems to have more potential. Instead of the extremely long tether envisioned in the previous concept, the center of mass of the tether is placed in a much lower orbit. If the tether were to simply dangle into the atmosphere from this orbit, however, it would have a hypersonic passage causing considerable drag and eventually pulling the tether from orbit. If, instead, the tether is counter-rotated so that as the lower end of the tether passes through the atmosphere it is traveling at sub-sonic speeds, the drag is reduced considerably, as is the amount of time the tether is subjected to this drag. A space launch vehicle can now be flown up to rendezvous with the end of the tether. The tether would be long enough to allow the appropriate atmospheric velocity and to reduce the centrifugal acceleration on injection into orbit. Such a tether would extend approximately 2,200 kilometers from the center of mass and would reach down to 12 kilometers above the earth's surface. Orbital altitude and angular momentum could be maintained by the use of high-efficiency, low-thrust engines (e.g., solar-powered ion or electrodynamic engines).

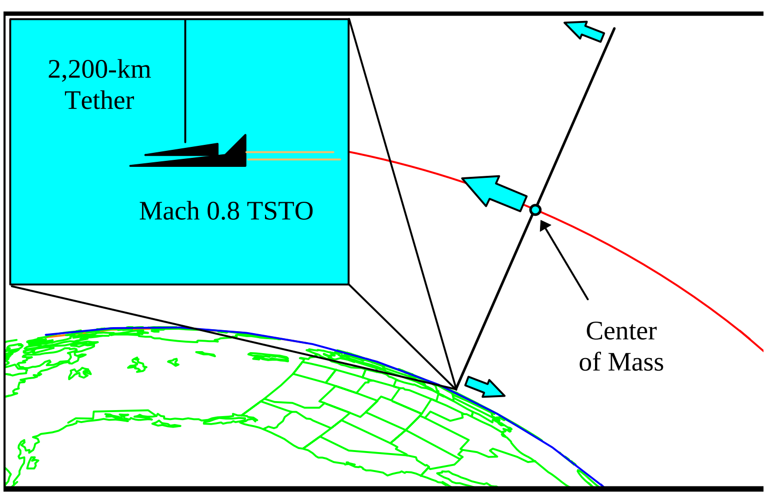

Figure 5. Rotating Tether

While the tether concept is conceptually simple, the construction and practical operation of such a system is filled with engineering challenges. Tether fabrication and deployment, characterization of its dynamic behavior, and development of techniques for successful docking represent a few of these challenges.

Recommendations

Based upon the results of this study, the following recommendations concerning high-leverage technologies supporting unconventional launch concepts are made:

- Research into high-energy-density fuels has the highest potential for payoff. Expansion of current technology development programs in this area should be a top priority.
- Research into advanced high-strength-to-weight materials benefits not only the construction of future tether systems but also the development of lighter, more durable spacecraft. Expansion of current materials development programs should also be a high priority.
- Research into nuclear engine design for launching payloads to low-earth orbit should be initiated.
- Research into the dynamics and design of tether systems should be continued.

THE SPACELIFT PROBLEM[16]
(ATTACHMENT)

The Problem

The fundamental problems facing our nation's ability to conduct routine space operations are the high cost and excessive delays now associated with conducting launch operations. Current information shows that it costs between $4,500 and $6,500 a pound to reach low-earth orbit (table 1). Furthermore, these numbers *only* reflect the price charged directly to the customer.

Launch Vehicle	Lift Capability (100 NM 28.5°)	Launch Price	Cost per Pound
Pegasus	1,000 lb	$7-$12 M	$7,000-$12,000
Taurus	3,200 lb	$15 M	$4,690
Titan II	5,000 lb	$43 M	$8,530
Delta 7925	11,100 lb	$45-$50 M	$4,050-$4,500
Atlas II	14,100 lb	$70-$80 M	$4,960-$5,670
Atlas IIA	14,900 lb	$80-$90 M	$5,370-$6,040
Atlas IIAS	18,500 lb	$110-$120 M	$5,950-$6,490
Titan IV	39,000 lb	$154 M	$3,950
Shuttle	51,800 lb	$130-$245 M	$2,510-$4,730

Table 1. Cost per Pound to LEO for Active US Launch Vehicles[17]

Recurring costs for the manpower required to launch the current US inventory of launch vehicles and the associated costs of operating our launch bases (table 2),

Launch Vehicle	Manpower Costs
Taurus	$100,000
Delta 7925	$3.3 M
Atlas II	$7.9 M
Titan IV	$48.0 M
Shuttle	$30-$84 M
Launch Sites	
Cape Canaveral AFS	$1.32 B/year
Kennedy Space Center	$2.16 B/year

Table 2. Manpower Costs[18]

suggest that the advertised prices for launch services do not cover recurring costs, much less amortize investment in R&D and infrastructure.

Launch Vehicle	Advertised Time to Launch	8-Hour Shifts
Pegasus	2 days	18
Taurus	5 days	Unknown
Delta 7925	23 days	102
Atlas II	55 days	115
Titan IV	100 days	190
Shuttle	150 days	240

Table 3. Launch Times

So, with launch services priced as they are, satellites must be built with the utmost in reliability, further driving up costs. The process of continual optimization and testing to ensure success drives up costs and drags out production schedules.

Schedules for preparing current launch vehicles and their payloads result in considerable delays in getting vital national assets on orbit (table 3). In many ways, the launch facility is the remote extension of the manufacturing facility. The product is not "finished" until pre-launch processing is complete. Not only do delays occur in launch processing, due primarily to a lack of standardized procedures, but they also occur in development due to the continual need for optimization. Since these systems are built to operate at maximum performance, safety margins are slim, causing further delays to improve the odds of success. All of these delays are major obstacles to the successful conduct of both military and commercial routine operations in space.

The need for timely assured access to space is particularly critical in the military arena. As the US moves into the next century, it will surely not be the only space power. Should it become embroiled in a conflict with another space power which leads to the destruction of on-orbit assets, the side which can reconstitute the capability derived from its lost assets the quickest will prevail. Even if the US does not go up against another space adversary, the current proliferation of nuclear weapons and ballistic missile technology makes it easy for an enemy, with no space assets to lose, to strike at and cripple near-Earth satellites with the launch of a single, unguided nuclear weapon. Furthermore, the expensive and unique launch infrastructure which currently limits US dispersion of launch resources to two launch bases, makes them extremely vulnerable to enemy attack, including terrorist attack. (Natural disasters, such as hurricanes or earthquakes, are other obvious risks to the launch infrastructure.)

There is an economic threat, as well. Since 1976, the US share of the commercial launch market has dropped from 100 percent to about 25 percent.[19] European, Russian, and Chinese launch prices are currently set at about half of what US launch services are. If the US is to remain competitive in this market, it *must* reduce launch prices considerably. The market is waiting to explode should a substantial drop in the price of launch services be realized, as evidenced by the recent announcement by the CEOs of Microsoft and McCaw Cellular Communications to deploy a network of 840 satellites to provide a global Internet.

Cost Considerations

Costs for operating any venture consist of fixed costs (one-time expenditures which do not change with changes in activity) and recurring costs (expenditures which vary based upon the activity level). To remain viable, a venture must cover recurring costs and amortize fixed costs over some reasonable period of time. For high-volume operations (such as the airlines), the key to profitability is to reduce recurring costs. For any operation, reducing fixed costs as a percentage of total operating costs is imperative, whether by reducing overall infrastructure or increasing the volume of operations.

To reduce costs in launch operations, any solution must have the goal of reducing the expensive, unique plant and equipment (e.g., launch processing facilities, extensive real estate holdings, and launch pads) together with the very large numbers of people required to maintain them. Recurring costs must also be reduced, particularly if spacelift operations are ever to be conducted anything like airlift operations.

Briefly contrasting current spacelift operations to airlift operations suggests that if airlift operations were conducted in the same manner as spacelift operations, each mission would begin with planning to determine payload characteristics well in advance of launch. The aircraft, which would be late-1950s vintage, would be selected to optimize performance based upon this payload, wasting as little performance margin as possible. Once the parts of the aircraft arrived at the airport, they would be wheeled out on the runway, one of the most expensive pieces of infrastructure, where the major components of the aircraft would be assembled and then the payload would be loaded. Since each operation is different, ground crews would have to improvise procedures for each takeoff. Because of the limited performance margins, any adverse weather conditions would delay takeoff. In the meantime, no other aircraft could takeoff or land on the runway. Once the aircraft was finally launched and delivered its payload, it would be scrapped.

When juxtaposed in this fashion, it is clear that this approach is severely flawed and in need of major changes. How did this situation result? Primarily because the US failed to make the same kinds of investments in developing safe, reliable, easy-to-use, reusable spacecraft that it did with aircraft. Instead, the US apparently has been content to continue using 40-year-old technology and proposing to use it for decades into the future. While some may judge these observations as unkind, they do not appear to be inaccurate.

So, how can these problems be resolved? Any solution solving the overall problem of reducing cost per pound to orbit must reduce recurring costs (use reusable launch vehicles) and eliminate or significantly reduce overall plant, equipment, and manpower costs. The latter can be done by standardizing and automating operations (thus reducing manpower) and *designing* the launch vehicle to operate from an existing infrastructure (such as the plant and equipment available at airports worldwide). This last point is crucial, since it will no more be politically or economically feasible to build special airports for a new aircraft than it will a new launch infrastructure for a new spacecraft. As can easily be seen, these are requirements that must be "built in" from the beginning.

Timeliness can also be improved by *designing* the launch system to be 'operational,' as well as designing in wider safety (performance) margins, thereby permitting launch under a broader range of conditions; and wider safety margins reduce overall development costs by reducing the need for extensive testing.

The US must push for fundamental changes in the way it conducts launch operations. Whatever it chooses to build must be simple to build and to operate. As noted in USSPACECOM Pamphlet 2-1, "In space warfare, as in all forms of warfare, the application of simplicity requires that plans conceived by geniuses must be executable by personnel who are not."[20] Therefore, any new system must be *designed* for automobile-type production and airline-type operations--either of which is capable of being performed by an average skilled technician. The goal for military space operations is to design systems and procedures so that launch vehicles can be maintained by well-trained high school graduates and operated by well-trained, non-scientific college graduates. Failing this, routine space operations remain an elusive goal.

Notes

[1]Fusion and antimatter also fall in this category.
[2]George P. Sutton, *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets*, New York: John Wiley & Sons, Inc., 1992 (Sixth Edition), p. 36.
[3]Section authored by Dr. Larry W. Burggraf and Dr. Davis E. Weeks, Department of Engineering Physics, Graduate School of Engineering, Air Force Institute of Technology.
[4]Calculation based upon a minimum-inclination launch into a 200-km altitude, 28.5° inclination orbit with 1 km/sec loss due to atmospheric drag.
[5]Peter Haaland, "High Energy Density Materials," *Critical Technologies for National Defense*, Washington, DC: American Institute of Aeronautics and Astronautics, 1991, pp. 281-282.
Section co-authored by Dr. William Bailey, Department of Engineering Physics, Graduate School of Engineering, Air Force Institute of Technology.
[6]Methane-Oxygen combustion yields 8 eV per reaction.
[7]Uranium-235 fission yields 200 MeV per reaction; Deuterium-Tritium fusion yields 18 MeV per reaction.
[8]Proton-Antiproton annihilation yields 1.876 GeV per reaction.
[9]Christopher Tarpley, Mark J. Lewis, and Ajay P. Kothari, "Radiation Safety Issues in Single-Stage-to-Orbit Spacecraft Powered by Antimatter Rocket Engines," *Journal of Propulsion*, Vol. 8, No. 1, Jan-Feb 1992, p. 127.
[10]Brice N. Cassenti, "Conceptual Designs for Antiproton Space Propulsion Systems," Journal of Propulsion, Vol. 7, No. 3, pp 368-373.
Christopher Tarpley, Mark J. Lewis, and Ajay P. Kothari, "Radiation Safety Issues in Single-Stage-to-Orbit Spacecraft Powered by Antimatter Rocket Engines," *Journal of Propulsion*, Vol. 8, No. 1, Jan-Feb 1992, pp. 127-135.
[11]Section authored by Dr. Kirk Mathews, Department of Engineering Physics, Graduate School of Engineering, Air Force Institute of Technology.
[12]Philip G. Hill and Carl R. Peterson, *Mechanics and Thermodynamics of Propulsion*, Reading, MA: Addison-Wesley Publishing Company, 1965, p. 478.
[13]Joseph A. Angelo, Jr. and David Buden, *Space Nuclear Power*, Malabar, FL: Orbit Book Company, Inc., 1985, pp. 177-196.
[14]Ibid, p. 195.
[15]Konrad E. Ebisch, "Skyhook: Another Space Construction Project," *American Journal of Physics*, Vol. 50, No. 5, May 1982, pp. 467-469.
Robert M. Zubrin, "The Hypersonic Skyhook," *Analog*, Vol. 113, No. 11, Sep 1993, pp. 60-70.

[16] Section authored by by Dr. Thomas Sean Kelso, Department of Operational Sciences, Graduate School of Engineering, Air Force Institute of Technology.
[17]Steven J. Isakowitz, *International Reference Guide to Space Launch Systems: 1991 Edition*, American Institute of Aeronautics and Astronautics, 1991.
[18]Steven J. Isakowitz, *International Reference Guide to Space Launch Systems: 1991 Edition*, American Institute of Aeronautics and Astronautics, 1991.
[19]*Ten-Year Space Launch Technology Plan*, National Space Council, November 1992, pp. 2-5.
[20] USSPACECOM Pamphlet 2-1, “United States Space Command: Doctrine for Space Control Forces,” 27 March 1990.