A Strategic Roadmap to Centauri

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ABSTRACT

This paper discusses the connectivity between in-space propulsion and in-space fabrication/repair and is based upon a workshop presentation by Les Johnson, manager of the In-Space Propulsion (ISP) Technology Project at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Ala.. Technologies under study by ISP include aerocapture, advanced solar-electric propulsion, solar-thermal propulsion, advanced chemical propulsion, tethers and solar-photon sails. These propulsion systems are all approaching technology readiness levels (TRLs) at which they can be considered for application in space-science and exploration missions. Historically, human frontiers have expanded as people have learned to "live off the land" in new environments and to exploit local resources. With this expansion, frontier settlements have required development of transportation improvements to carry tools and manufactured products to and from the frontier. It is demonstrated how ISP technologies will assist in the development of the solar-system frontier. In-space fabrication and repair will both require and assist the development of ISP propulsion systems, whether humans choose to settle planetary surfaces or to exploit resources of small Solar System bodies. As was true for successful terrestrial pioneers, in-space settlement and exploitation will require sophisticated surveys of inner and outer Solar System objects. ISP technologies will contribute to the success of these surveys, as well as to the efforts to retrieve Solar System resources. In a similar fashion, the utility of ISP products will be greatly enhanced by the technologies of in-space repair and fabrication. As in-space propulsion, fabrication and repair develop, human civilization may expand well beyond the Earth. In

the future, small human communities (preceded by robotic explorers) may utilize these techniques to set sail for the nearest stars.

1. Introduction

This paper demonstrates that, barring breakthroughs, co-related progress in the fields of in-space propulsion, fabrication and repair will ultimately lead to the capability of expanding human exploration and civilization towards the nearest extra-solar star system. An early version of this paper was presented by L. Johnson at the In-Space Fabrication and Repair Workshop, which was coordinated by the NASA Headquarters' Physical Science Research Division and conducted at the Marshall Institute in Huntsville, Alabama, July 8-10, 2003. An extended version of the presentation will soon be published as a NASA Technical Memorandum [1].

The major focus of this paper is the connectivity of on-going in-space propulsion research performed by the In-Space Propulsion (ISP) Technology Project at NASA's Marshall Space Flight Center (MSFC) to in-space fabrication and repair prospects. ISP is an outgrowth of the NASA Interstellar Initiative of the late 1990's. It has broadened its initial focus from a concentration on the solar-photon sail to include aerocapture, advanced solar-electric propulsion (SEP), solar-thermal propulsion (STP), advanced chemical propulsion and tethers, as well as the solar sail [2].

Mission possibilities for these technologies have also broadened from heliopause probes [3] to include a host of scientific Solar System missions. ISP is currently supported by the NASA Science Mission Directorate in Washington and is directed to perform basic and long-term research leading to the development of advanced in-space transportation technologies.

One way to characterize the relative maturity of selected technologies investigated by ISP is the Technology Readiness Level (TRL) system [4]. The TRL system, which is summarized in Table 1, provides a summary view of the maturation process for new space technologies. Figure 1 presents circa-2003 TRLs for the in-space propulsion options under investigation by ISP.

NASA managers and engineers utilize the TRL system to prioritize various in-space propulsion options [5]. High-Priority Technologies include aerocapture, next generation SEP and solar-photon sails. Medium-Priority Technologies include advanced chemical rockets, high-power (multi-kilowatt) SEP and STP. High-Risk, High-Payoff and Lower-Priority Technologies include momentum-exchange tethers and the ultra-thin solar-photon sail (areal mass thickness < 1 g/m^2). Some basic research is also underway to ascertain the ultimate feasibility of solar-plasma sailing [2,6].

Current aerocapture research emphasizes the integration of a low-mass aeroshell with a thermal-protection system and the development of aerocapture instrumentation. In a typical aerocapture application, an interplanetary spacecraft would dip into a planet's outer atmosphere, using drag to decelerate the vehicle for capture as a satellite of that planet.

As currently envisioned, the next generation of SEP ion thrusters will include a number of technological innovations. Two of these are the NASA Evolutionary Xenon Thruster, or NEXT, and the application of carbon-based ion optics. High-power (kilowatt-level) SEP research includes laboratory demonstrations of low- and high-power (up to 50-kW) Hall thrusters.

Solar-photon sail research and development is concentrated on subsystem design and fabrication, as well as ground demonstration. Structural testing of sail booms is underway, as is the evaluation of the long-term effects of exposure of ultra-thin sail material to the space environment. Research on ultra-light sails consists of the investigation of ultra-low-mass sail materials; large-area, low-mass structures; and the trades involved in Earth-launch versus space fabrication.

Work on momentum-exchange tethers emphasizes model development and evaluation. Consideration is being given to the design of the catch mechanism necessary to exchange momentum between a rotating tether and a payload, and research on high tensile-strength tethers.

A number of aspects relating to advanced chemical rockets are also under study. These include fuel development, consideration of cryogenic fluid management and development of low-mass components.

With the possible exception of advanced chemical rockets, all of the in-space propulsion technologies under study by ISP have one commonality. At least in part, they utilize existing atmospheric or interplanetary resources (solar-photon momentum and energy, the geomagnetic field, etc.) to “live off the land.” If research in advanced chemical rockets leads to the capability to build rocket components from extraterrestrial resources or mine extraterrestrial Solar System bodies for fuel, this technology will also be capable of ”living off” the interplanetary “land.” All these technologies, therefore, may be instrumental in the expansion of terrestrial civilization into the extraterrestrial realm.

2. Historical Perspective

A good starting point for any discussion of the possible future expansion of civilization into and beyond the Solar System is a review of successful terrestrial exploration and settlement efforts. It is obvious from such a review that exploration, exploitation and settlement expansion are not unique to the current phase of human existence.

Starting from a "Garden of Eden" in or near present-day Kenya in equatorial Africa, pre-human hominoids began their spread into northern Africa, Europe and Asia more than one million years ago. Without the discovery of fire, which allowed the ancestors of modern humanity to apply *in situ* resources to functions such as food preparation and habitat heating, expansion into temperate and polar climates would have been impossible.

Early "civilized" humans continued this tradition of "living off the land" as their habitats expanded [7-9]. Minoan, Mycenaean, Phoenician and Dorian/Ionian Greek colonies were established when population pressures encouraged emigration from parent cities to the "frontier." In order to survive in their new environments, the successful ancient settlers quickly learned to exploit the resources of the lands in which their new homes were situated.

One wonders how far pre-classical civilization would have spread if sea-going vessels always required oar-power, instead of depending upon local wind. When a colonization vessel crossed an ocean, as opposed to an inland sea, the injunction to "live off the land" became even more stringent. If the Polynesians had been required to carry all their food with them instead of fishing off the sides of their ocean-going canoes, or if early European settlers in the "New World" had not adapted to native foods (such as the wild turkey), the range of human settlement today would certainly not be global.

In the early years of the 19th century, most of the population of the United States was huddled close to the Atlantic Ocean. Thomas Jefferson, perhaps the most visionary of the early American presidents, initiated the era of western expansion by commissioning the 1804 Lewis and Clark expedition. The Lewis and Clark "Corps of Discovery," which commenced in May 1804 from a camp near St. Louis and culminated in September 1806, reached the Pacific Ocean while traversing approximately 13,000 kilometers of previously unmapped terrain [10-12].

Without this preliminary exploration, westward-bound settlers would have had no idea of the local resource base required to insure their survival, let alone their capability to establish thriving continental population centers. Geographical knowledge regarding the interior of the North American continent was primitive before the Lewis and Clark expedition -- President Jefferson was far from unique in his hope that the Corps of Discovery would locate a water route to the Pacific.

The Corps of Discovery numbered 48 men. Supplies were transferred up the Missouri River via riverboat and smaller vessels. Overland portage was also necessary, which required the minimization of supply weight. It was, therefore, necessary for expedition participants to satisfy much of their food requirements by hunting.

Corps members were aided by Sacagawea, a Native American, and her husband Toussaint Charbonneau, a French-Canadian interpreter. With their help, members of the Lewis and Clark Expedition learned how to further supplement their diets with local vegetation, such as camas roots.

The success of the Lewis and Clark Expedition led to the opening up of the North American continental interior to settlement and exploitation. Continental settlement would have been a good deal slower and less successful, if an efficient mode of carrying settlers and their baggage westward and frontier produce eastward did not exist.

This transport mode -- the Conestoga Wagon and related Prairie Schooner (so-called because of its boat-shaped body and tall, white canvas bonnet) -- satisfied the requirements of westward expansion and eastward continental transport during the first half of the 19th century [13,14].

Capable of carrying loads up to eight tons (approximately 7300 kilograms) with the motive force provided by teams of horses, oxen or mules, these vehicles were for decades the principle trading "ships" of the North American prairie. Typically three meters or more in length, these wagons were equipped with tool kits so that repairs could be made *en route*, hundreds of kilometers from the nearest mechanic's shop.

Although Prairie Schooners opened up the frontier, they had certain drawbacks. They couldn't be depended on to keep to a rigid timetable; they were uncomfortable for their human passengers; and they were very hard on their animal "engines." As the population of the frontier and the volume of transcontinental traffic increased, development and application of a more efficient transportation mode became necessary.

The introduction of the Transcontinental Railroad provided a vast improvement over the Prairie Schooner. Initially employed in the late 19th century for military purposes, the first American tracked vehicle was constructed in 1826 [15]. During that year, the feasibility of the steam-powered locomotive was demonstrated on a circular track in Hoboken, New Jersey by John Stevens [16].

Although early American railways were local, private ventures usually constructed to connect eastern population centers, the construction of the Transcontinental railroad was a much vaster undertaking. This monumental project, surveyed by the U.S. Army Topographic Corps, required the support of the Federal Government and was finally completed in 1869 [17]. The resulting linkage of the North American continent opened the western frontier to large-scale settlement and exploitation.

Those seeking to open and develop the space frontier could learn a great deal from this earlier terrestrial experience. In a successful exploration/exploitation/settlement enterprise, there is ample room for both private and public initiatives. Successful pioneers must learn how to "live off the land" and to exploit local materials and resources as quickly as possible to reduce the requirement for re-supply. A major justification for resource surveys prior to settlement is the necessity to know what the local resource base is and how best to exploit it.

3. In-Space Propulsion and "Living-Off-The Land"

Application of new in-space propulsion technologies will allow interplanetary explorers and pioneers to exploit local resources and "live off the land" in a manner analogous to that of successful terrestrial pioneers. One near-future application of these technologies to interplanetary pioneering may be *in-situ* propellant manufacture.

ISP technologies can also 'live off the land' in a number of other manners. Sunlight can be used to propel solar photon sails and SEP and STP technologies, as well as provide energy for space settlers; the solar wind might be applied to drive solar plasma sails (if these prove feasible); and Earth's magnetosphere can be utilized for orbit-changing purposes by the electrodynamic tether.

Local material application for purposes other than propellant manufacture will result in the utilization of planetary regolith for cosmic radiation shielding. Local water ice can provide a source of water and oxygen, and local minerals can be mined for fabrication and energy-production [18].

3.1 In-Situ Propellant Manufacture

The rate of human civilization's expansion into the Solar System will be greatly increased if chemical rocket fuel can be manufactured from in-situ resources on or near the surfaces of various Solar System destinations. Various options exist to accomplish this task.

3.1.1 Mining the Moon

If the Moon has ample deposits of cometary water in Sun-shaded craters near the lunar poles, future lunar explorers will be able to refuel their spacecraft, using sunlight to dissociate water into oxygen and hydrogen. Evidence for large-scale, water-ice deposits in lunar polar craters is, however, ambiguous.

Clementine-mission bistatic-radar results have been interpreted as demonstrating that permanent water-ice deposits exist near the lunar South Pole [19]. These results were apparently confirmed by a neutron spectrometer aboard *Lunar Prospector*. However, radar-reflection studies performed using the Arecibo radio telescope in Puerto Rico show no evidence of water ice [20].

At the end of its useful life, *Lunar Prospector* was directed to crash into a crater near the Moon's South Pole. Spectroscopic observations during the controlled crash failed to confirm the presence of lunar water [21]. The jury on the existence of lunar water has clearly not yet reached a verdict.

Even if water ice is not a large-scale lunar resource, some Moon rocks are 40 percent oxygen [20]. It is not impossible that future lunar expeditions could carry a supply of hydrogen from Earth and mine oxygen from lunar regolith or bedrock. Since hydrogen is a much smaller mass fraction of water than oxygen, such a strategy could significantly reduce the mass delivered to the lunar surface to support the expedition.

3.1.2 Mining Mars

The dominant molecular species in Mars' thin atmosphere is CO_2 [20]. Hydrogen oxides, including water, exist in the atmosphere and on the surface of Mars.

Zubrin et al [22] have proposed that terrestrial explorers or settlers on Mars could produce rocket propellant by combining hydrogen transported from Earth with Martian CO_2 to produce methane and water. Electrolysis would be used to dissociate the water into hydrogen and oxygen. Methane and oxygen could then be reacted and exhausted as a rocket fuel. If ongoing studies demonstrate conclusively that water is abundant on or just below Mars' surface, this process would be greatly simplified.

3.1.3 Asteroid / Comet Mining

Resource-mining techniques considered for application on the Moon and Mars could also be utilized to refuel spacecraft visiting small Solar System bodies. Spectroscopic studies have revealed that water vapor is a significant component of comet tails and comas near the Sun; and ice layers must be present on comets closer to aphelion [20].

Although asteroid samples have not yet been returned to Earth by spacecraft, meteorites have delivered asteroid fragments to Earth. One class of meteorite -- carbonaceous chondrites -- is typically about 40 percent oxygen and two percent hydrogen by weight. Interestingly, Mars' small satellites Deimos and Phobos are suspected to be similar to carbonaceous chondrites. Although hydrogen may be rare in parent bodies of other meteorite types, model studies reveal oxygen is a major constituent [20].

3.2 Solar-Electric Propulsion and Space Habitation / Fabrication

Inspired by the "High Frontier" concept of Gerhard K. O'Neill, a number of researchers have proposed that large orbiting space habitats and fabrication facilities could be constructed from lunar and/or asteroidal material [23-25]. This proposal represents a classic example of bootstrapping.

Reusable or partially reusable Earth-to-orbit transportation would first be utilized to establish an initial space manufacturing facility in Low Earth Orbit (LEO). A feedstock of tools, machine parts and biosphere components would be delivered to this facility. A low-thrust drive, such as SEP, might then be used to deliver mining equipment and personnel to the Moon or a near-Earth asteroid.

Materials mined from this object would then be used to construct large in-space habitats and solar-power stations. Energy beamed back to Earth from the solar-power stations would be the initial industrial product of this space-based infrastructure.

O'Neill space habitats would have dimensions of the order of kilometers and masses of billions of kilograms. Most of the mass requirement, which is dictated by the necessity to shield space-habitat dwellers from galactic cosmic rays, would be satisfied using lunar or asteroidal resources. The environment inside the habitats, which would rotate to simulate gravity, would be as earthlike as possible.

Solar-power satellites would also be large. These would consist of millions of kilograms of kilometer-dimension, thin-film panels to convert sunlight into electricity and a microwave array to transmit the gigawatts of electrical power back to Earth.

SEP is an enabling technology for the "High Frontier" proposal. SEP research will result in highly efficient and reliable solar-electric thrusters that could maintain large space manufacturing facilities (SMF) in LEO, with much greater cost effectiveness than conventional chemical rockets, due to the much higher SEP exhaust velocity. SEP will also find application in the transfer of equipment, personnel and manufactured material through space.

The "mass driver" is a technology that has been positively influenced by SEP research. Mass drivers, which have undergone small-scale breadboard tests, are essentially solar-powered electromagnetic catapults that could fling mined materials from the Moon or an asteroid towards an orbital processing/manufacturing facility.

3.3 Electrodynamic Tethers and Space Fabrication

Another ISP technology product with application to in-space fabrication is the electrodynamic tether [26-28]. As shown in Fig. 2, an electrodynamic tether can be used to reboost a Space Manufacturing Facility located in LEO, without the use of on-board propellant. Such a tether, constructed from a long, conducting strand, would be oriented so that the lower end is attached to the SMF. Electrons are collected from the Earth's upper ionosphere, near the position of the space facility. Powered by the SMF solar cells, the collected electrons are pushed up the tether and emitted at a higher altitude than the facility's orbit. Since the entire system is within Earth's magnetosphere, the resulting electrodynamic thrust force on the tether's unidirectional current adds energy to the SMF orbit, thereby raising its orbital height and compensating for atmospheric drag.

3.4 The MXER Tether and Inter-Orbital Transfer

Another tether concept with possible application to the development of the space frontier is the MXER (Momentum-eXchange/Electrodynamic Reboost) tether, which is a hybrid of momentum-exchange and electrodynamic tether designs [29]. A rotating momentum-exchange tether can increase the orbital energy of a payload by releasing it near the tether's farthest height above Earth. But the orbital energy of the tether itself decreases during this maneuver, and its orbital height is consequently reduced.

After the payload is released from a MXER tether, the tether's rotation is slowed. A solar-power station attached to the conductive tether is then used to direct a unidirectional current through the tether, as shown in Fig. 2. This process increases the tether's orbital height. Both maneuvers -- payload transfer to higher orbit and tether-station orbit raising -- are accomplished without the expenditure of propellant.

Near-future MXER tethers could rendezvous with payloads of LEO or sub-orbital launches and transfer them to Geostationary Earth Orbit (GEO) or Earth-escape trajectories. To accomplish this feat, the tether must initially be in an elliptical orbit with its rotation timed so the tether tip is oriented vertically below the solar-power station at its center-of-mass and is swinging backward at the perigee of its orbit. A grapple on the lower tether tip captures the payload from its low-orbit location and releases it half an orbit later.

Farther in the future, tethers could be applied as shown in Fig. 3 to create an extraterrestrial equivalent of the transcontinental railroad. Here, a LEO-tether sends a payload to a tether in orbit around the Moon. Approaching the Moon, the payload will rendezvous with a lunar tether, which then deposits it upon the lunar surface and/or picks up a payload to be returned to Earth.

3.5 Solar-Thermal Propulsion (STP) and In-Space Fabrication

The solar-thermal rocket functions by using collected and focused sunlight (or laser light) to heat a propellant working-fluid such as hydrogen [30,31]. The specific impulse of the STP typically ranges from 800 to 1,000 seconds, about twice that of the most energetic existing chemical rocket. The comparatively high thrust and propellant efficiency enables 30-day trips from LEO to geostationary earth orbit (GEO).

As the space frontier develops, STP could see application as a space tug equivalent in the transfer of equipment and manufactured products between space manufacturing facilities in LEO and higher orbits. The technology used in the low-mass STP, sunlight-focusing optics may also see application in SMF furnaces used for large-scale on-orbit manufacturing.

4. Deep-Space Resources: Survey and Retrieval

Before the settlement of the space frontier beyond Earth orbit can commence, the space-age equivalent of the Lewis and Clark expedition must take place. Even after 47 years of space travel, the human knowledge base of Solar System resources is not yet adequate to plan the settlement, development and exploitation of deep space.

4.1 The Humanized Solar System

The Solar System is an enormous place, both in space and time. Earth's nearest neighbor in space, the Moon, is at an average distance of 384,000 km. After achieving Earth-escape velocity (about 40,000 km/hr), Apollo astronauts required approximately three days to travel one-way between Earth and the Moon [32].

Venturing beyond the Moon, an explorer next encounters near-Earth Objects (NEOs). Suspected to be of asteroidal and cometary origin, some of these objects occasionally approach Earth within cis-lunar distances. Known NEOs range in diameter between a few hundred meters and a few kilometers [20].

Some NEOs can be visited on round-trip trajectories, requiring less energy than landings on the Moon. Round-trip travel time to some low-inclination, low-eccentricity NEOs has been estimated to be a year or less [18]. NEOs have collided with Earth many times in geological history -- such an impact may have doomed the dinosaurs 65 million years ago. To prolong the lifetime of human civilization and the human species, space-faring institutions must devote attention to the problem of predicting and preventing NEO impacts [33].

Although humans may settle and mine the Moon and NEOs, inclement surface and atmospheric conditions may preclude such activity on Venus, which is about 30 percent closer to the Sun than is the Earth. Because of the high-energy solar orbit required to reach an object deep within the Sun's gravity well, small, hot Mercury may also be off limits to human activity for the foreseeable future.

The nearest planet of interest for potential human occupation is, of course, Mars. The fourth planet from the Sun [with a mean solar distance of about 1.5 Astronomical Units (AU)], Mars is in a fairly elliptical solar orbit. Even very energetic propulsion technologies require several months for a one-way trip to the "Red Planet." Most one-way voyages to Mars require six to nine months [34]. Mars' two tiny satellites, Deimos and Phobos, may also be of interest as "way stations" for Martian explorers.

Traveling beyond Mars, an explorer would next encounter the "Main Belt" (MB) asteroids, which are located between about 2.2 and 3.3 AU from the Sun. The largest of these irregular shaped minor planets, Ceres, is approximately 1,000 km in diameter [20].

Data from space probes and terrestrial telescopes reveals that some of these asteroids have smaller satellites. Some are rocky; others are stony. A third class of these MB asteroids is carbonaceous chondrites, which may contain some water reserves.

One-way travel to low-inclination, low-eccentricity MB asteroids is approximately a year, using contemporary propulsion systems. As the development of the Solar System proceeds, the mining of MB asteroids will become increasingly significant.

One-thousandth the mass of the Sun and 318X the mass of the Earth, giant Jupiter orbits 5.2 AU from the Sun. Like the other gas giants, Jupiter is surrounded by a ring system and accompanied by many satellites. Some of these satellites are captured asteroids and comets. The four largest -- Callisto, Europa, Ganymede and Io -- were observed by Galileo at the dawn of telescopic astronomy and most likely formed with Jupiter.

Life may exist beneath the frozen oceans of Europa. Other Jovian satellites may serve as an outer-Solar System resource base, provided human and robotic explorers in this realm can be shielded against Jupiter's intense radiation belts. Travel from Earth to Jupiter, along a minimum-energy trajectory, requires about 2.7 years [32].

Farther out from the Sun, the explorer next encounters the smaller gas giants, Saturn, Uranus and Neptune. Each is considerably more massive than the Earth and is equipped with many satellites and rings. The most magnificent ring system, of course, is Saturn's. Saturn is accompanied by Titan, the only satellite in the Solar System that possesses a dense atmosphere.

Ranging from Neptune's orbit (30 AU) to about 50 AU from the Sun is another zone of small Solar System bodies -- the Kuiper Belt Objects (KBOs). Pluto (about 1200 km in radius) is the largest discovered KBO. These objects are sometimes dubbed "cometoids" because of their apparent similarity to icy comets [20]. Current-technology flybys of KBOs require a decade or longer. Decelerated rendezvous or sample-return missions to these very distant objects will require either considerable improvements in propulsion technology or much-longer mission durations.

Although at least some of the short-period comets are KBOs affected by giant-planet gravitational perturbations [35], most comets reside in the Oort Cloud. As many as 10^{12}-10^{13} comets may exist in this vast reservoir, with a total mass as high as 30 Earth masses. Some long-period comets have aphelia greater than 20,000 AU and require more than 10,000 years to orbit the Sun [20]. Even with significant advances in propulsion technology, robotic expeditions to Oort Cloud objects will require many decades.

4.2 Destinations and Resources

Low-gravity objects- -- near-Earth Objects, small planetary satellites, Main Belt asteroids, Kuiper Belt Objects and Oort Cloud objects -- will provide the basic resource base for an expanding in-space infrastructure. The reason for this is accessibility. It will be easier to mine these low-gravity objects than to enter a planet's gravity well, establish a surface manufacturing/mining facility and launch the manufactured or mined product back into space through that planet's gravity well.

The *in-situ* exploration of these minor Solar System bodies has begun. Table 2 lists Solar System bodies visited to date, as well as the spacecraft visiting these small bodies. Reference 20 describes the physical properties of many of the objects visited.

A number of other missions are currently underway or scheduled for the near future. Utilizing SEP, the Japanese Hayabusa (Muses-C) probe was launched in 2003 towards Asteroid 25143 Itokawa. Plans call for station-keeping near the asteroid, a soft landing and return of retrieved samples to Earth in 2007

In March 2004, the much larger European Rosetta probe was launched towards an encounter with Comet 67P/Churyumov-Gerasimenko in 2014. Rosetta is scheduled to orbit this comet and deposit a lander on the comet's surface.

The first non-governmental deep-space exploration mission, the Near-Earth prospector (NEAP) is scheduled for launch in 2006-2008. The mission for this probe is being planned by SpaceDev, Inc.

NASA recently launched Deep Impact towards Comet Tempel 1. This spacecraft will split into two components -- one will slam into the comet's nucleus, and the other will spectroscopically analyze the ejecta at close range.

4.3 Propulsion: Required Improvements and Options

In-space propulsion technology advances will greatly expand the deep space resource knowledge-base. Such advances, coupled with reduced spacecraft size and mass and increased solar cell efficiency, will allow space probes to venture further into the Solar System with more scientifically productive payloads. Decreased mission costs resulting from these improvements should lead to more frequent exploratory expeditions to a wider variety of destinations and/or decreased mission durations.

Increases in SEP specific impulse will reduce propellant requirements, increase payload allotment and/or decrease interplanetary-transfer time. Improved solar cells with increased energy-conversion efficiency and decreased mass should allow for the possibility of solar-powered, resource-survey missions deeper into the asteroid belt.

When the solar-photon sail becomes operational, it may become the preferred propulsion system for out-of-ecliptic missions [36]. Even early solar sails could be used to rendezvous with NEOs in high-inclination solar orbits. With increased thermal tolerance, sail-propelled probes could explore comets within the orbit of Mercury. Departing from elliptical solar orbits with perihelia <1 AU or low-perihelion solar orbits [9,36], sails could propel payloads on fast flybys of KBOs. Decreased sail areal mass thickness and increased sail thermal tolerance may allow such flybys of objects in the nearer Oort Cloud.

Advances in aerocapture technology should allow the development of aeroshells of lower mass and greater thermal tolerance. One can imagine advanced aerocapture missions decelerated by Neptune's atmosphere for rendezvous with KBOs near that giant planet [37,38].

Improvements in chemical rocket technology may include higher specific impulse, greater reliability and longer in-space storage time. Certain classes of rendezvous and sample-return missions will be positively impacted by these developments.

Tether improvements will include better understanding of tether dynamics and interaction with the space environment. Since tethers may prove very useful in reducing the cost of orbit-transfer, they may improve performance of some deep space survey missions. A tether could be used, for example, to raise the orbital height of a solar-photon sail unfurled in LEO to an altitude less affected by atmospheric drag. Another technology that may compete for lower-cost inter-orbit transfer is STP.

4.4 Resource Retrieval Via Solar Sail

After accessible Solar System resources are surveyed and mining techniques developed, methods must be developed to economically transfer mined resources across the Solar System in a manner analogous to freight railways. Drexler was one of the first researchers to consider the solar sail for this application [40].

Current-generation Earth-launched solar sails typically have an areal mass thickness of about 0.01 kg/m^2. These sail films are typically tri-layered, with the sunward side being a reflective material (usually aluminum), the back (anti-sunward) side an emissive material (such as chromium) and a plastic substrate in between [36].

To create a solar sail, in-space analog to a freight railroad, it will be necessary to reduce the sail areal mass thickness by about an order of magnitude. There are several possible ways to do this.

Drexler proposed vapor-phase deposition as a method of creating thin metallic films in space [40]. A second possibility is to launch a metal/plastic bi-layer sail from Earth with the plastic substrate constructed of a UV-sensitive material that would evaporate in space [41]. Another option is the application of a super-strong, hyper-thin and heat-resistant Earth-launched fabric-type sail [42]. As proposed by Forward [43] and further developed by Matloff [44], another possibility is a perforated-nanomesh sail.

Much further research is required to ascertain which of these techniques is superior for this application or if another approach should be selected. But it is not unreasonable to expect 22nd century "clipper ships" with multi-kilometer sails crisscrossing the "prairies" of the Solar System with their cargoes of asteroidal and cometary material (Fig. 4).

The "parachute" sail shown in Fig. 4 is, of course, not the only sail configuration that might be chosen for this application [9,37]. As well as the development of ultra-thin sail materials that are very long-lived in the space environment, it will be necessary to utilize cables (or alternative supporting structure) of the highest possible tensile strength. Various approaches, such as hydrostatic beams, have been suggested to reduce the mass of the supporting structure for a large solar sail [45].

5. Propulsion-System Fabrication Using In-Space Resources

Another connection between space manufacturing and in-space propulsion is the possible in-situ fabrication of components for propulsion systems at space manufacturing facilities. Drexler's proposal [40] to produce ultra-thin solar sails in space using vapor-phase deposition is an example of this concept.

With the application of Rapid Prototyping (RP) technology, many additional propulsion system fabrication possibilities emerge. Rapid Prototyping has been described as the three-dimensional equivalent of a Fax [46]. A prototype of a machine part or tool is first designed using a Computer-Aided Design (CAD) package. The RP machine then quickly constructs the prototype layer by layer using powder, liquid or sheets of material. After the prototype is constructed and approved, a cast is produced from which final products and parts can be constructed in quantity.

After early experimental work in the 1980's, RP was utilized in the 1990's by Rocketdyne (Canoga Park, Calif.) to design and construct precision parts of rocket engines. This new technology reduces prototyping cost and time considerably.

A space manufacturing facility could exploit RP as follows. Lunar regolith or raw asteroidal material would first be gathered and then separated by element or compound. This material would serve as the feedstock for the RP machine, which would construct precision propulsion system components using on-board CAD equipment. Repair and replacement engine parts could thereby be constructed using in-space resources, reducing the need for re-supply from Earth.

6. Conclusions: The Far Future

After the connectivity of in-space propulsion, fabrication and repair has opened the frontier of the Solar System, the enhanced human in-space infrastructure may be applied to more ambitious goals. Two of these goals are the robotic exploration of interstellar space and the expansion of human civilization beyond the Solar System.

The first institutional study of the feasibility of interstellar travel was Project Daedalus, which was conducted by the British Interplanetary Society between 1974 and 1978 [47]. Follow-on research continues to be published in various venues, including the "Interstellar Studies" section of this journal.

After the conclusion of Project Daedalus, study coordinators Alan Bond and Anthony Martin published several papers concluding that the only feasible approach to interstellar travel by humans was the "worldship" [48]. A worldship would be a mobile version of the self-sufficient, closed-ecology, Earth-approximating space habitats discussed by O'Neill and others [23-25] and would be capable of transferring a small human population to the vicinity of a nearby star on a voyage approximating a millennium.

It was also concluded in these studies [48] that only two propulsion systems might ultimately be feasible for worldship acceleration -- the nuclear-pulse rocket and the ultra-thin solar sail. As discussed by Dyson [49], nuclear-pulse rockets are propelled by the detonation of high-yield nuclear or thermonuclear "devices" behind a pusher plate coated with ablative material and/or protected by a charged-particle-reflecting magnetic field. Although ultimately feasible technically, the nuclear-pulse rocket has obvious political and sociological acceptance issues.

The interstellar solar sail was investigated before 1980 by NASA Jet Propulsion Laboratory (JPL) researcher Chaucey Uphoff, who incorporated his results in the JPL Thousand Astronomical Units (TAU) study [50]. TAU was a study of a robotic probe to 1,000 AU from the Sun that could be accomplished using projected early 21st century technology. The concept has been further elaborated by Matloff and Mallove [9, 51-53].

After launch from Earth or construction in space, the interstellar sailcraft is maneuvered into an elliptical or parabolic solar orbit with a perihelion as close to the Sun as possible. At perihelion, the sail is unfurled and oriented towards the Sun and the spacecraft is accelerated by solar radiation pressure to a heliocentric velocity higher than the solar-escape velocity.

In the original concept, the sail was oriented normal to the Sun during the post-perihelion acceleration. As Giovanni Vulpetti has argued [54], in some cases there are advantages to non-constant, non-normal solar-aspect angles.

If one assumes space-manufactured, metallic monolayer sails with thickness approximating 20 nm; thermally-limited approaches to the Sun within 0.01-0.04 AU; and diamond-strength cables, modeling results reveal that interstellar travel times to the nearest extrasolar star system (Alpha Centauri at 4.3 light years or 270,000 AU) approximates 1,000 years even for very large payloads [52].

Peak accelerations exceed 1 g (one Earth-surface gravity) for some optimized trajectories. As demonstrated in a finite-element study by Cassenti et al [55], at least some sail configurations can withstand accelerations as high as 2.5 g.

One advantage of this approach to interstellar travel is sail versatility. After acceleration, the sail and cables can be wrapped around the habitat section of the worldship to provide cosmic-ray shielding. If the target star is solar-type (as are both the Alpha Centauri central stars), the sail can be unfurled again near the destination star and used for deceleration [9].

Human technological capabilities are not yet up to the in-space manufacture of 100-km dimension, ultra-thin metallic sails or the ultra-strong cables required to connect the worldship and sail. Astronomy is not yet capable of surveying the planets (if any) that accompany the Alpha Centauri stars. Our knowledge of closed ecological systems and the long-term stability of small, isolated human populations is far from complete.

Although planning a multi-generation mission to a nearby star is premature, early extrasolar probes propelled by the solar sail have received increasing attention. This is perhaps because it is relatively easy to scale down a worldship sail into an extrasolar-probe sail.

Inspired in part by the NASA JPL TAU study and the ultimate prospects of sail-launched interstellar worldships, European researchers considered -- during the 1990s -- sail-launched extra-solar probes to the Sun's gravitational focus at 550 AU and the heliopause at 200 AU [56,57]. In the late 1990s, this work was incorporated into the NASA Interstellar Probe (ISP) study [58].

NASA should have the technological capability to launch early solar-photon-sail interstellar precursor probes before 2020. If the areal mass thickness of the sail films approaches 0.001 kg/m^2, and the sail material can withstand a perihelion of about 0.2 AU, a disc sail with a radius of about 200 m should be able to project 30-kg science payload (100-kg total payload) spacecraft on a voyage to the heliopause at 200 AU from the Sun that would take no more than two decades. Such a craft could reach the inner-gravitational focus of the Sun at 550 AU within a human lifetime.

Later in the 21st century, sail advances should allow humanity the capability to explore the inner Oort Cloud at 1,000-2,000 AU on flights with durations approximating a human lifetime. This may be the best possible performance with an Earth-launched sail.

Advances in space manufacturing should eventually lead to the ability to construct solar-photon sails in space that are close to the physically minimal film thickness. Experience with space-mining techniques should offer the opportunity to fabricate such sails using in-space resources, as well as the application of many sail architectures.

Additional advances to be expected in the 21st century include maintenance of closed or nearly-closed eco-systems in space. Experience with small space crews on long-duration explorations beyond LEO should offer data to sociologists regarding long-duration stability of small, isolated human communities.

There is no reason, therefore, that the capability to perform multi-generation interstellar voyages will not arise as a natural consequence of development of the Solar System. Hopefully, new technologies such as beamed-energy sailing [43,59] will greatly reduce interstellar-voyage durations before humans begin to expand towards the stars.

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References

1. L. Johnson, D. Harris, A. Trausch, G. L. Matloff, T. Taylor and K. Cutting, "In-Space Propulsion: Connectivity to In-Space Fabrication and Repair," NASA TM
2. T. McElyea, A *Vision of Future Space Transportation*, Apogee Books, Ontario, Canada (2003).
3. L. Johnson and S. Leifer, "Propulsion Options for Interstellar Exploration," AIAA-2000-3334.

4. J. C. Mankins, "Technological Readiness Levels," http://advtech.jsc.nasa.gov/downloads/TRLs.pdf (April 6, 1995).

5. "Integrated In-Space Transportation Plan (IISTP) Phase II Final report," Contract GS-23F-0107J, Order No. H-35186D, Science Applications International Corp., Huntsville, Ala. (July 31, 2002).

6. R. Winglee, J. Slough, T. Ziemba and A. Goodson, " Mini-Magnetosphere Plasma Propulsion (M2P2): High Speed Propulsion Sailing the Solar Wind," presented at STAIF 2000 Conference, University of New Mexico, Albuquerque, N.M. (January 30-February 3, 2000).

7. R. B. Lee, "Models of Human Colonization: San, Greeks, and Vikings," in *Interstellar Migration and the Human Experience*, B. R. Finney and E. M. Jones eds., University of Chicago Press, Berkeley, Calif. (1985), pp. 180-195.

8. B. R. Finney, "Voyagers in Ocean Space," in *Interstellar Migration and the Human Experience*, B. R. Finney and E. M. Jones eds.., University of Chicago Press, Berkeley, Calif. (1985), pp.164-179.

9. G. L. Matloff, *Deep-Space Probes*, Springer-Praxis, Chichester, UK.

10. J. P. Ronda, *Lewis and Clark Among the Indians*, University of Nebraska Press, Lincoln, Neb. (1984).

11. J. P. Ronda, *Voyages of Discovery: Essays on the Lewis and Clark Expedition*, Montana Historical Society Press, Helena, Mont. (1998).

12. J. P. Ronda, Microsoft™ Encarta™ Online Encyclopedia 2004, http://encarta.msn.com, Microsoft Corporation, Redmond, Wash. (2004).

13. "Conestoga Wagon," *Britannica Concise Encyclopedia*, http://www.britannica.com/ebc/article?eu=386677, Encyclopedia Britannica premium service, Chicago, Ill. (2004).

14. "Conestoga Wagon," *The Columbia Encyclopedia*, Sixth Ed., http://www.bartleby.com/65/co/Conestog.html, Columbia University Press, N.Y. (2003).

15. D. J. Boorstin, *The Americans: the Democratic Experience*, Random House, N.Y. (1965).

16. T. W. Van Metre, *Transportation in the United States*, Foundation Press, Brooklyn, N.Y. (1950).

17. C. L. Wheat, *Mapping the Transmississippi* West, vols. 1-5, Institute of Historical Cartography, San Francisco, Calif. (1957-1963).

18. M. Sonter, "Near-Earth Objects as Resources for Space Industrialization," *Solar System Development Journal*, **1**, 1-31 (2001).

19. S. Nozette, C. L. Lichtenberg, P. Spudis, R. Bonner, W. Ort, E. Malaret, M. Robinson and E. M. Shoemaker, "The Clementine Bistatic Radar Experiment, " *Science*, **274**, 1495-1498 (1996).

20. K. Lodders and B. Fegley, Jr., *The Planetary Scientist's Companion*, Oxford University Press, Oxford, UK (1998).

21. D. Isbell, D. Morse, and B. Rische, "No Water Ice Detected from Lunar Prospector Impact," NASA Press Release 99-119, http://nssdc.gsfc.nasa.gov/planetary/text/lp_pr_19991013.txt

22. R. Zubrin, S. Price, L. Mason, and L. Clark, "Report on the Construction and Operation of a Mars In-Situ Propellant Production Unit," AIAA-94-2844, 30th AIAA, ASME, SAE, ASEE Joint Propulsion Conference and Exhibit, Indianapolis, Ind. (June 27-29, 1994).

23. G. K. O'Neill, "The Colonization of Space," *Physics Today*, **27**, No. 9, 32-40 (Sept. 1974).

24. G. K. O'Neill, *The High Frontier*, Morrow, N.Y. (1977).

25. R. D. Johnson and C. Holbrow eds., *Space Settlements: A Design Study, NASA SP-413*, NASA, Washington, D.C. (1977).

26. R. R. I. Samanta, D. E. Hastings, and E. Ahedo, "Systems Analysis of Electrodynamic Tethers," *Journal of Spacecraft and Rockets*, **29**, 415-424 (1992).

27. V. V. Beletskii and E. M. Levin, "Electrodynamic Tethers," *Dynamics of Space Tether Systems, Advances in the Astronautical Sciences*, **83**, Univelt, San Diego, CA (1993), pp. 267-332.

28. R. D. Estes, E. C. Lorenzini, J. Sanmartin, M. Martinez-Sanchez, C. L. Johnson and I. E. Vas, "Bare Tethers for Electrodynamic Space Propulsion, " *Journal of Spacecraft and Rockets*, **37**, 205-211 (2000).

29. K. F. Sorensen, "Conceptual Design and Analysis of an MXER Tether Boost Station," AIAA 2001-3915, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, Utah (July 8-11, 2001).

30. J. M. Shoji and P. E. Frve, "Solar Thermal Propulsion for Orbit Transfer," AIAA 88-3171, 24th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Boston, Mass. (July 11-13, 1988).

31. G. Grossman and G. Williams, "Inflatable Concentrators for Solar Propulsion and Dynamic Space Power," *Journal of Solar Energy*, **112**, 229-236 (1990).

32. R. R. Bate, D. D. Mueller, and J. E. White, *Fundamentals of Astrodynamics*, Dover, N.Y. (1971).

33. S. Ostro and C. Sagan, "Cosmic Collisions and Galactic Civilizations," *Astronomy and Geophysics*, **39**, 422-424 (1998).

34. K. Sankaran, L. Cassady, A. D. Kodys, and E. Y. Choueiri, "A Survey of Propulsion Options for Cargo and Piloted Missions to Mars," *Annals of the New York Academy of Sciences*, **1017**, 450-467 (2004).

35. E. Belbruno and B. G. Marsden, "Resonance Hopping in Comets," *Astronomical Journal*, **113**, 1433-1444 (1997).

36. C. R. McInnes, *Solar Sailing*, Springer-Praxis, Chichester, UK (1999).

37. G. L. Matloff, "Persephone: A Non-Nuclear Rendezvous Mission to a Kuiper Belt Object," in Proceedings of Space Technology and Applications International Forum—STAIF 2000, ed. M. S. El-Genk, American Institute of Physics, College Park, Md. (2000).

38. G. L. Matloff and T. Taylor, "The Solar Sail as Planetary Aerobrake," IAC-03-S.6.02, 54th IAC Congress, Bremen, Germany (September 29—October 3, 2003).

39. G. R. Schmidt, H. P. Gerrish Jr., J. J. Martin, G. A. Smith, and K. J. Meyer, "Antimatter Production for Near-Term Propulsion Applications," presented at NASA/JPL/MSFC/AIAA Tenth Annual Advanced Space Propulsion Workshop, Huntsville, Ala. (April 5-8, 1999).

40. K. E. Drexler, "High Performance Solar Sails and Related Reflecting Devices," AIAA-79-1418, 4th Conference on Space Manufacturing Facilities, Princeton, N.J. (May 14-17, 1979).

41. S. Santoli and S. Scaglione, "Project Aurora : A Preliminary Study of a Light, All-Metal Solar Sail," in *Missions to the Outer Solar System and Beyond, 1st IAA Symposium on Realistic, Near-Term Scientific Space Missions*, ed. G. Genta, Levrotto & Bella, Turin, Italy (1996), pp. 37-48.

42. G. Garner, B. Diedrich, and M. Leipold, "A Summary of Solar Sail Technology Developments and Proposed Demonstration Missions," AIAA-99-2607, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Los Angeles, Calif. (July 21-23, 1999).

43. R. L. Forward, "Starwisp: An Ultralight Interstellar Probe," *Journal of Spacecraft and Rockets*, **22**, 345-350 (1985).

44. G. L. Matloff, "The Perforated Solar Sail: Its Application to Interstellar Travel," *JBIS*, **56**, 255-261 (2003).

45. G. Genta and E. Brusca, "The Parachute Sail with Hydrostatic Beam: A New Concept for Solar Sailing," *Acta Astronautica*, **44**, 133-140 (1999).

46. A. Doyle, "Pioneering Prototypes," *Computer Graphics World*, **23**, No. 9, 39-47 (September, 2000).

47. A. Bond. A. R. Martin, R. A. Buckland, T. J. Grant, A. T. Lawton, H. R. Mattison, J. A. Parfait, R. C. Parkinson, G. R. Richards, J. G. Strong, G. M. Webb, A. G. A. White, and P. P. Wright, "Project Daedalus: The Final Report on the BIS Starship Study," *JBIS*, supplement to **31**, S1-S132 (1978).

48. A. R. Martin, "World Ships—Concept, Cause, Cost, Construction, and Colonization," *JBIS*, **37**, 99-116 (1984).

49. F. Dyson, "Interstellar Transport," *Physics Today*, **21**, No. 10, 41-45 (October, 1968).

50. L. D. Jaffe, C. Ivie, J. C. Lewis, R. Lipes, H. N. Norton, J. W. Stearns, L. D. Stimpson, and P. Weissman, "An Interstellar Precursor Mission," *JBIS*, **33**, 3-26 (1980).

51. G. L. Matloff and E. F. Mallove, "Solar-Sail Starships—The Clipper Ships of the Galaxy," *JBIS*, **34**, 371-380 (1981).

52. G. L. Matloff and E. F. Mallove, "The Interstellar Solar Sail: Optimization and Further Analysis," *JBIS*, **36**, 201-209 (1983).

53. E. F. Mallove and G. L. Matloff, *The Starflight Handbook*, Wiley, N.Y. (1989).

54. G. L. Matloff, G. Vulpeti, C Bangs, and R. Haggerty, "The Interstellar Probe (ISP): Pre-Perihelion Trajectories and Application of Holography," NASA/CR-2002-211730.

55. B. N. Cassenti, G. L. Matloff, and J. Strobl, "The Structural Response and Stability of Interstellar Solar Sails," *JBIS*, **49**, 345-350 (1996).

56. J. Heidmann and C. Maccone, "ASTROsail and SETIsail: Two Extrasolar Missions to the Sun's Gravitational Focus," *Acta Astronautica*, **37**, 409-410 (1994).

57. G. Vulpeti, "The Aurora Project: Flight Design of a Technology Demonstration Mission," in *Missions to the Outer Solar System and Beyond, 1st IAA Symposium*

on Realistic Near-Term Scientific Space Missions, ed. G. Genta, Levroto & Bella, Turin, Italy (1996), pp. 1-16.

58. L. Johnson and S. Leifer, "Propulsion Options for Interstellar Exploration," AIAA-2000-3334, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Ala. (July 16-19, 2000).

59. R. L. Forward, "Round-Trip Interstellar Travel Using Laser-Pushed Lightsails," *Journal of Spacecraft and Rockets*, **21**, 187-195 (1984).

TABLE 1: *The Technological Readiness Level (TRL) System*

TRL 1:	**Basic Principles Have Been Observed and Reported;**
TRL 2:	**Technology Concepts And/or Applications Have Been Formulated;**
TRL 3:	**Analytical / Experimental Proof-of-concept Research Has Been Performed;**
TRL 4:	**Component And/or Breadboard Laboratory Validation Has Been Performed;**
TRL 5:	**Component And/or Breadboard Validation Tests in Relevant Environment Have Been Performed;**
TRL 6:	**System /Subsystem Prototype/model Demonstration in Relevant Environment Has Been Performed;**
TRL 7:	**System Prototype Function Has Been Demonstrated in a Space Environment;**
TRL 8:	**Completed System Flight Qualified Through Ground/space Demonstration;**
TRL 9:	**Completed System Flight Proven Through Successful Space Mission Operations.**

TABLE 2: *Minor Solar-System Bodies Visited by Spacecraft. All missions used chemical propulsion and were fly-by or fly-through unless otherwise noted.*

Solar System Object	Spacecraft Name	Country Origin	Year of Exploration
Halley's Comet	Giotto	Europe	1986
	ISEE-3 / ICE	USA	
	Vega 1 & 2		
	Sakigake & Suisei	Japan	
MB Asteroid 951 Gaspra	Galileo	USA	1991
Comet P/Griggs-Skejellerup	Giotto	Europe	1992
MB Asteroids 243 Ida / Dactyl	Galileo	USA	1993
MB Asteroid 253 Mathilde	NEAR	USA	1997
MB Asteroid 1992 KD (Braille)	Deep-Space 1*	USA	1999
NEO Asteroid 433 Eros**	NEAR	USA	2000
Comet Borrelly	Deep-Space 1*	USA	2001
Comet Wild***	Stardust	USA	2004

* *First deep-space application of SEP.*

** *Orbit and soft-landing.*

*** *Samples collected, Earth-return scheduled for 2006.*

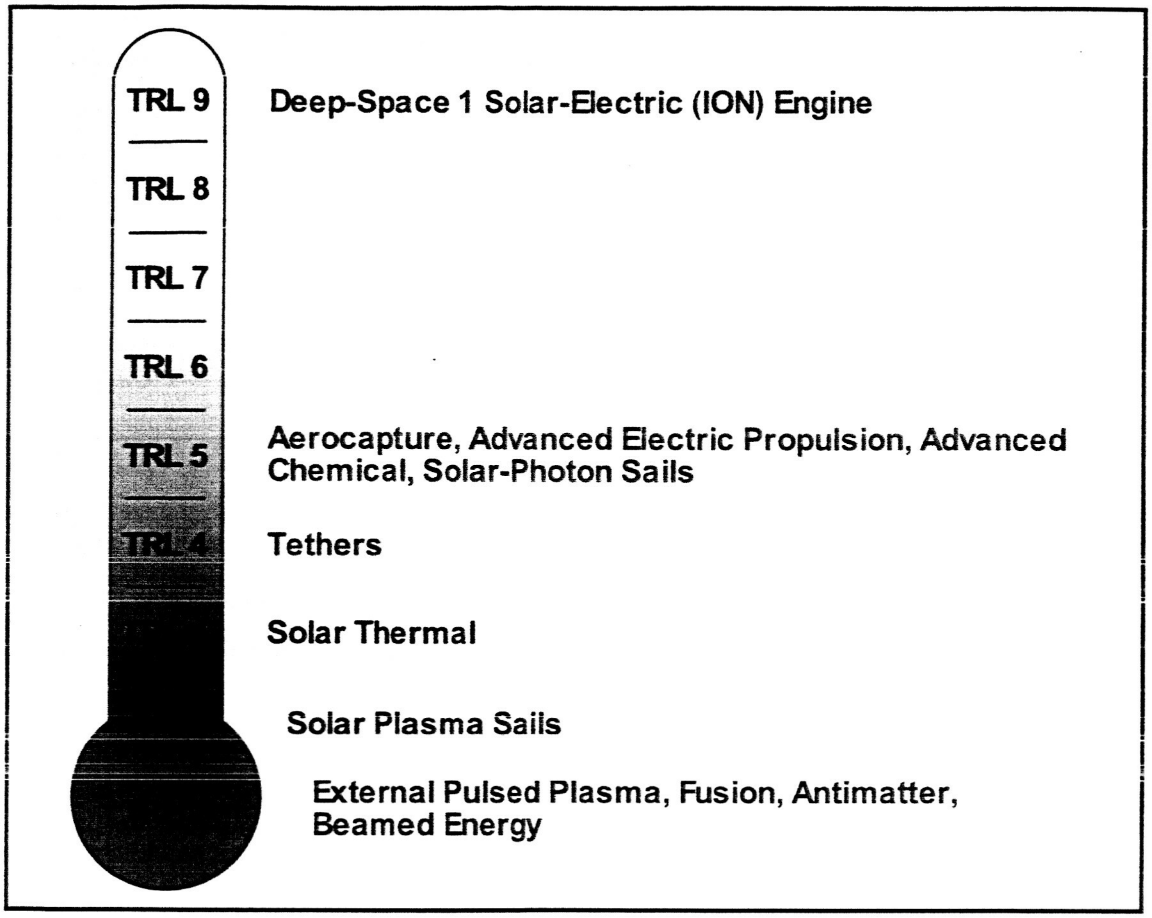
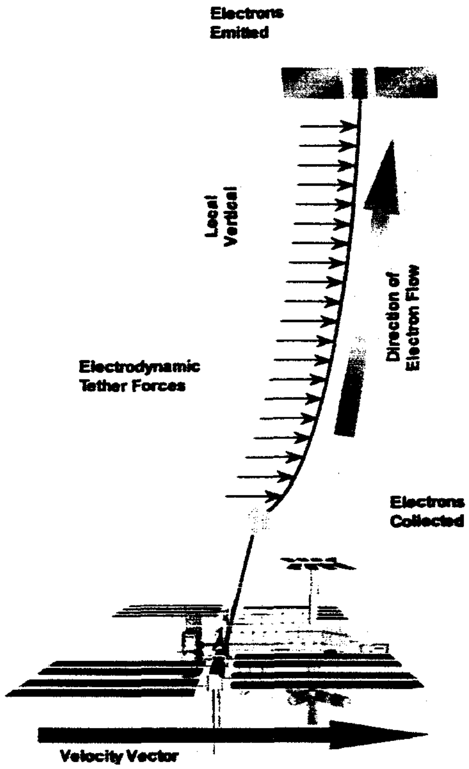


Fig. 1. Estimated TRLs for Various In-Space Propulsion Options, as of July 2004

How In-Space Propulsion Can Support In-Space Fabrication and Repair (Mid-Term)



- **Using the environment of LEO, large facilities can be reboosted electrodynamically, requiring no propellant or resupply**
  - $F = I\, dL \times B$
    - F = Thrust Force
    - I = Current extracted from the ionosphere
    - L = Length of conducting tether
    - B = Earth's magnetic field

Fig. 2. Application of an Electrodynamic Tether to Raise the Orbit of an SMF in LEO.

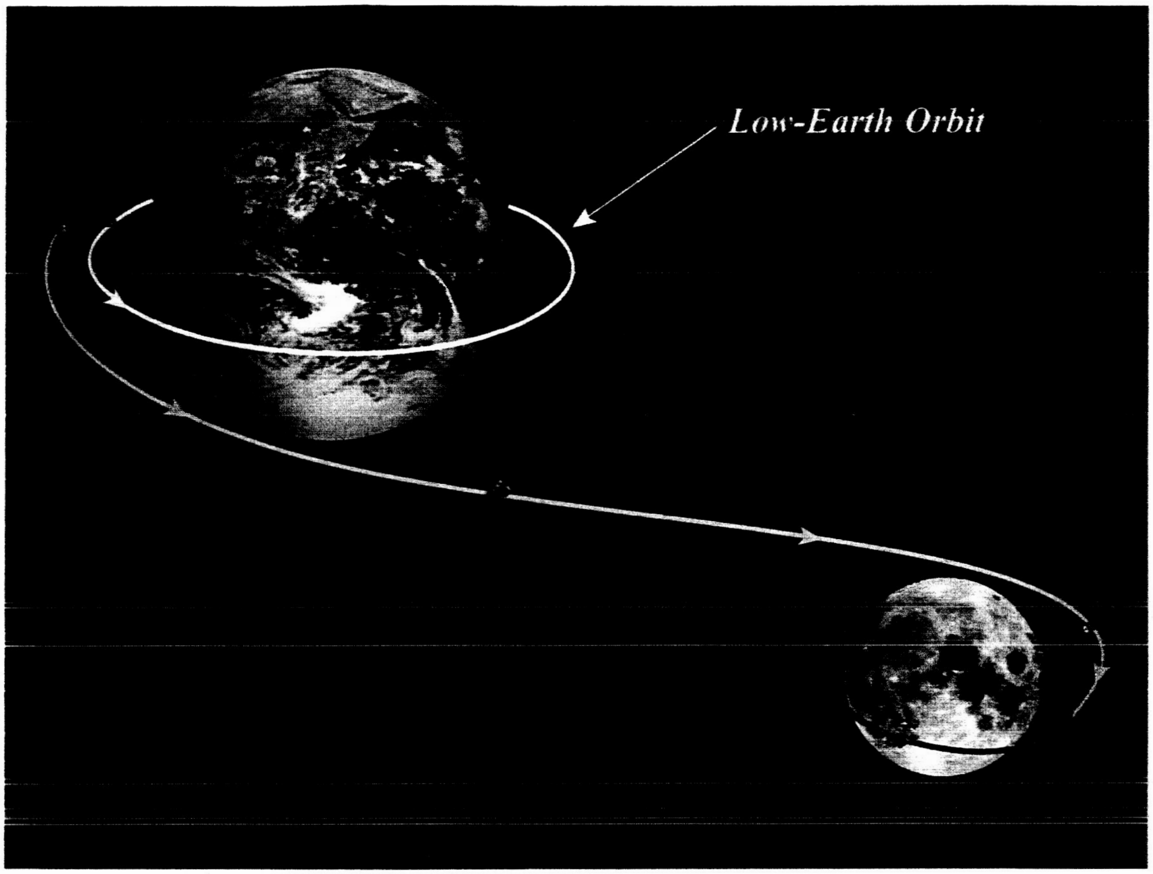


Fig. 3. A Tether Equivalent to the Railroad.

Lunar Payloads could be delivered to the surface of the Moon with just two tethers. The payload is launched from Earth and is picked up by a tether in low Earth orbit. This spinning tether throws the payload to GEO or places it on an Earth-escape trajectory. At the Moon, it is picked up by another tether in orbit there. This lunar tether then deposits the payload onto the Moon's surface or picks up a payload for the return trip.

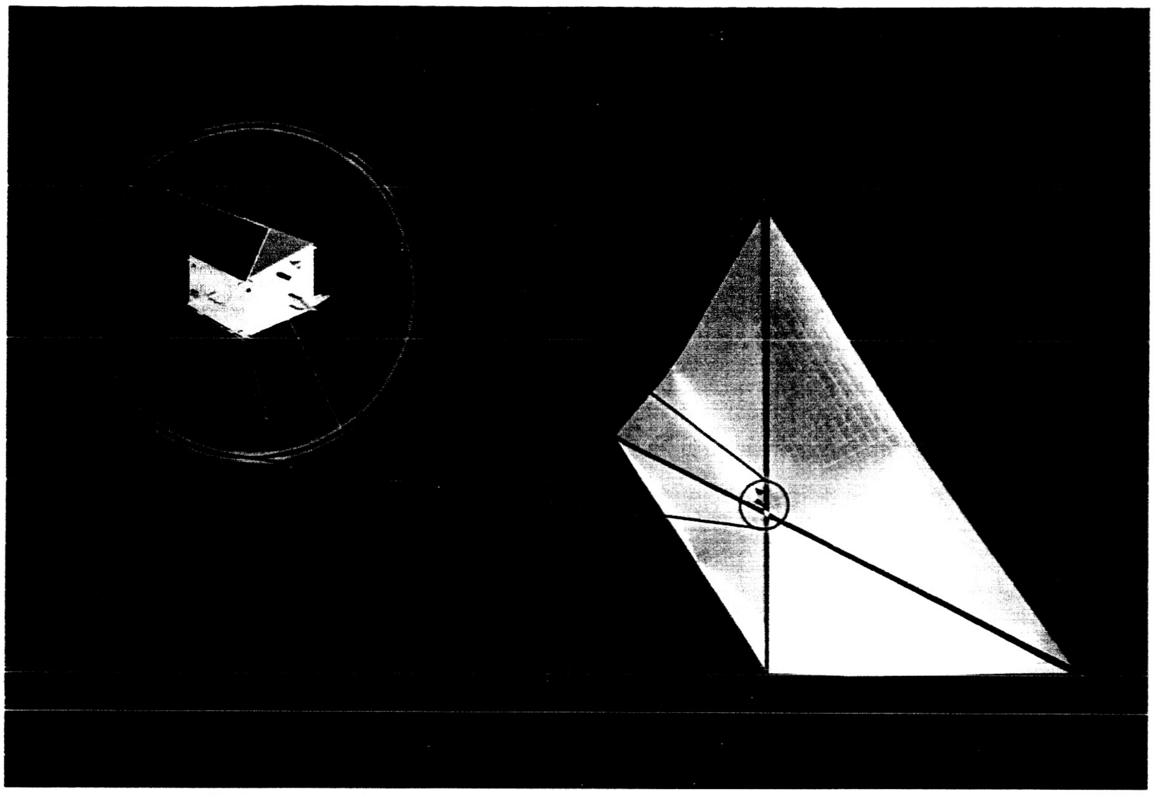


Fig. 4. A Future Solar-Sail Freighter. The Sun is to the Left.