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EXOTIC POWER AND PROPULSION CONCEPTS

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ABSTRACT

The status of some exotic physical phenomena and unconventional spacecraft concepts that might produce breakthroughs in power and propulsion in the 21st Century are reviewed. The subjects covered include: electric, nuclear fission, nuclear fusion, antimatter, high energy density materials, metallic hydrogen, laser thermal, solar thermal, solar sail, magnetic sail, and tether propulsion.

INTRODUCTION

Chemical rockets have opened up space, landed humans on the Moon, put robotic landers on Venus and Mars, and sent flyby probes past all the major planets and moons in the solar system. All this despite the fact that any physicist can prove than any known chemical fuel doesn't have enough energy content to raise even itself into orbit, much less take any payload with it. Propulsion engineers proved the physicists wrong by designing multiple stage vehicles with extremely high mass ratios that reached 622:1 for the Saturn V moon rocket liftoff mass vs. the capsule mass that parachuted back to the Earth's surface.

If the United States decides it wants to construct a space defense, set up a lunar base, or explore Mars, then chemical rockets can do those jobs. But because of the relatively low specific impulse of chemical propellants, and the high overall mass ratios they imply for these difficult missions, the cost for accomplishing these tasks will be so high it is very likely that the United States will decide not to do the mission at all. If we are going to return to the Moon, explore Mars, and open up the solar system to rapid, economical travel, we need to find a method of propulsion that is an improvement over standard chemical rocket propulsion. That is the goal of that amorphous field of aerospace engineering called "advanced space propulsion".

NUCLEAR PROPULSION

If the public can be sold on the idea of using nuclear propulsion for future space missions--fine. Proceed using that technology and ignore the rest of this paper. I suspect, however, that despite its real lack of danger and its great savings in cost and time, the nuclear rocket will not be a politically viable method of space travel. I will therefore write the rest of this paper and I encourage you to read it.

Nuclear Thermal Propulsion
Nuclear thermal propulsion is an advanced propulsion technology capable of producing thrust-to-weights greater than unity at high specific impulses of typically 825 seconds (nearly twice that of liquid-oxygen/liquid-hydrogen). Nuclear rockets were demonstrated to be feasible in the ROVER and NERVA solid core fission reactor test programs from 1959 to 1972, but unfortunately they were killed for political and budgetary reasons before they ever got off the ground. A summary of nuclear thermal rocket development and testing experience is covered in reference 1.

Fusion Propulsion
Since the nuclear fusion process typically converts three times as much mass to energy as the nuclear fission process, it has long been recognized that fusion fuels are much more energetic than fission fuels. Fusion propulsion is a wonderful idea, but its time has yet to come. Researchers still have not demonstrated a self-sustained controlled fusion reaction on the ground, and the reactor designs presently being funded by the Department of Energy are more suitable for massive power plants than lightweight rocket engines. That doesn't stop the advanced propulsion advocates from looking at new fusion propulsion concepts and designing new, lightweight fusion rockets. Whether these lightweight designs can ever be made self-sustaining is problematic, considering all the work put in on their larger power plant cousins.

Robert W. Bussard at EMC^2 has proposed (ref. 2) a low thrust fusion electric propulsion system that uses his Riggatron compact tokamak fusion reactor design designed operate on the difficult D-D fusion reaction. This reaction produces tritium, helium-3, and a fast neutron. The neutrons escape to space, while the hot (10-40 keV) tritium and helium-3 plasma is extracted at 30 atm pressure and mixed with a large amount of hydrogen gas diluent propellant to produce a high specific impulse exhaust. Bussard also speculates on an "electrostatic fusion propulsion" system using the reaction $p + {}^{11}B \rightarrow 3\ {}^{4}He$. In principle, the fusion product energy can be converted directly into electric power by causing the charged helium ions to expand against an electric field. This would result in a fusion-electric propulsion option with high specific impulse and high thrust.

V.E. "Bill" Haloulakas at McDonnell-Douglas and Bob Bourque at General Atomics carried out an Air Force Astronautics Laboratory sponsored study (ref. 3) of a $D\text{-}{}^{3}He$ fusion rocket using pulsed translating compact toroids that borrows from the DoE spheromak program. Again, thermal energy from the plasma heats a hydrogen propellant to obtain the optimum specific impulse.

In a combination of two technologies, Cerald Smith of Penn State has shown that antiprotons impinging on uranium atoms create fission nearly 100% of the time, releasing 180 MeV of fission fragment energy in the target. Under JPL sponsorship, Smith is now studying the use of small amounts of antimatter to trigger fission in the uranium shell of a pellet, which in turn will trigger fusion in the D-T mixture in the center of the pellet.

Antiproton Annihilation Propulsion

Antimatter propulsion is one of the long range, high risk, high payoff propulsion technologies. A series of studies (ref. 4 to 9) have shown that antimatter propulsion is not only physically and technologically feasible, it can be both cost effective and mission enabling. When antiprotons meet normal protons, all of the mass of both particles is released, not as gamma rays, but as elementary particles called pions. Two-thirds of those energetic particles are charged, and studies have shown that it is possible to extract a significant percentage (30-50%) of the energy as thrust (see Fig. 1). The optimized mass ratio of an antimatter rocket for any mission is typically 3:1, independent of the antimatter energy utilization efficiency or the mission ΔV. This low mass ratio enables missions that cannot be done using any other propulsion technique. The amount of antimatter needed for all missions within the solar system is measured in milligrams.

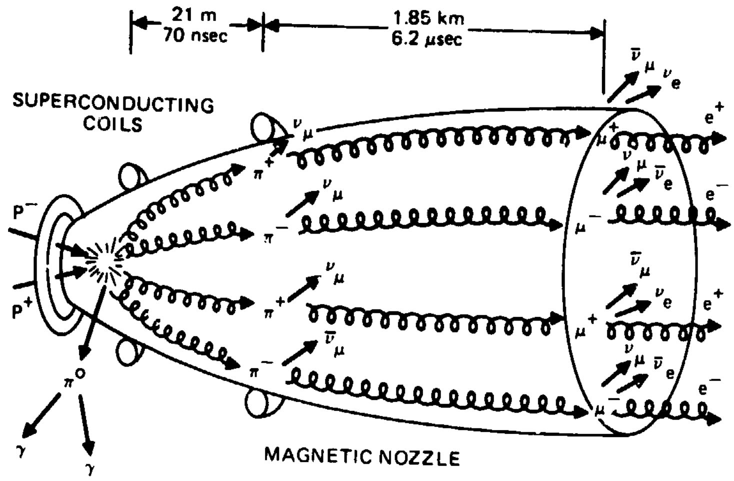

Fig. 1 - Schematic of Generic Antimatter Rocket

For example, Giovanni Vulpetti of Telespazio (ref. 10) has designed a re-usable SSTO antimatter powered vehicle with a dry mass of 11.3 tons, payload of 2.2 tons, and 22.5 tons of propellant for a lift-off mass of 36 tons (mass ratio 2.7:1). This vehicle can put 2.2 tons of payload in GEO and bring back a similar 2.2 tons, while using 10 milligrams of antimatter. Moving 5 tons of payload from low Earth orbit to low Martian orbit with a 18 ton vehicle only requires 4 milligrams of antimatter.

The only source of low energy antiprotons is at CERN, in Switzerland. But Fermi National Accelerator Laboratory or Brookhaven National Laboratory could be modified to produce low energy antiprotons for less than $25 million. Ted Kalogeropolous at Syracuse has shown that present production quantities of antiprotons already are sufficient for non-destructive evaluation of rocket nozzles, as well as imaging and treatment of cancer tumors. Brian Von Herzen has formed the Antimatter Technology Corporation to commercially develop these medical applications.

The RAND Corporation has sponsored two Antiproton Science and Technology workshops (ref. 11) that found no showstoppers to antimatter propulsion, but determined that producing adequate quantities (grams per year) would require two successive generations of dedicated antiproton production facilities, a pilot plant to prove economic feasibility, followed by a large production plant. Realistically, this will take 30 years and 30 billion dollars, but it could save many hundreds of billions in the cost of future national space initiatives.

The present experimental effort in the field is concentrated on the capture and storage problem. Gerald Gabrielse of Harvard led an international team to CERN, captured 60,000 antiprotons in a cryogenic, ultrahigh vacuum electromagnetic trap no larger than a demitasse cup, and kept them trapped for 50 hours (ref. 12). The next step is adding positrons and making antihydrogen. The Air Force Astronautics Lab is looking into the growth of charged antihydrogen cluster ions as a method of condensing the antihydrogen while maintaining it in a trap. Under JPL sponsorship, George Seidel at Brown University is solving the problems of levitating milligram sized balls of antihydrogen ice. Since the electromagnetic and mechanical properties of hydrogen and antihydrogen are the same, the research is being carried out using normal hydrogen.

Antimatter rockets are a form of nuclear rocket. Although they emit insignificant amounts of neutrons, and the engines do not present a long term radiation hazard as do nuclear thermal rocket engines, they do emit gamma rays when operating, and require proper shielding and stand-off distance precautions. Unfortunately, the word "antimatter" still evokes raised eyebrows, mental images of Star Trek, and stifled giggles from upper level decision makers in the advanced propulsion branches of NASA and the Air Force. If they would read the scientific literature and be willing to consider technologies other than those that will produce results during their short time in office, they would find a new propulsion technology that could open up the solar system.

EXOTIC CHEMICAL FUELS

High Energy Density Materials (HEDM) is the new Holy Grail of the chemical propulsion community. All the chemical elements are known, and nearly all the possible combinations of those elements into molecular compounds are known. Over the centuries since the Chinese invented gunpowder, there has been a continuing life-or-death motivation to find the most energetic of those compounds for use in propelling projectiles and rockets. To date, the most energetic fuel we have (that isn't deadly poisonous) is liquid-oxygen/liquid-hydrogen, which produces a maximum specific impulse of 500 seconds. Some would say there are no new chemical propellants to be found. The goal of the HEDM program is to somehow find a new chemical material with both a high energy density and a low molecular weight.

The major HEDM effort in the United States is at the Applied Research In Energy Storage (ARIES) Office at the Air Force Astronautics Laboratory, with another large effort in basic research being funded out of the Air Force Office of Scientific Research. A 1986 outgrowth of Project Forecast II, the Air Force HEDM program is putting more than $5 million a year into 50 R&D projects around the world. They hold annual contractors conferences where the results of the previous year are shared with the research community (ref. 13-15). There are a number of ways to increase the energy density of a fuel: Add light metals as atoms or small clusters, trap the energy of an excited electronic or vibrational state, force molecules to form highly strained bonds, and condense the material into a denser form.

Metastable helium fuel, made of electronically excited helium atoms (the easily-formed active ingredient in a helium-neon laser), has a projected specific impulse of 3100 seconds. The practical lifetime of metastable helium is less than one second, although theory projects an ideal lifetime of eight years. Early in the HEDM effort, Jonas Zmuidzinas of JPL investigated variations involving metastable helium molecules and solid metastable helium metal, with no positive results. No active research in this area is known of at this time.

Tetrahydrogen (an excited state molecule with four hydrogen atoms in a tetrahedron-shaped molecule) initially also looked promising, but detailed calculations on large computers showed it had a rapid-acting decay channel, verifying why it is not found in nature. The study of this system has led to other candidates, such as a-N_2O_2 (asymmetric nitrous peroxide), Li_3H, FN_3, and B_2Be_2. Theoretically, B_2Be_2 has a heat of formation of 238 kcal/mole and when unimolecularly decomposed gives a specific impulse of over 600 seconds. FN_3 has been prepared, is stable at low temperatures, and in addition to being an interesting monopropellant, also seems to have applications as a short wavelength chemical laser fuel and a high explosive!

Spin-polarized atomic hydrogen with a potential specific impulse of 2100 seconds has been produced in the laboratory by Daniel Kleppner of MIT in quantities large enough to cause damaging explosions in cryogenic glassware, but the lifetime of the atoms decreases drastically with density, due to an increase in three-body recombination collisions. Unless a way is found around this problem, it will not produce a usable fuel.

Unconventional molecules with "strained" bonds, such as variations on cubane (a cube made of carbon atoms with 90 degree bonds instead of the normal 180 degree linear carbon bonds) are being studied, both by supercomputers and test tube. Something may come of this research, but the increase in specific impulse over that of LOX-hydrogen will not be great.

Metallic hydrogen, a dense form of atomic hydrogen with a specific impulse of 1700 seconds and a density of 1.15 g/cc (compared to 0.07 g/cc for liquid molecular hydrogen), looks promising. H.K. Mao and R.J. Hemley at Carnegie Institution have used diamond anvil presses to apply pressures up to 300 GPa (3 Mbar) to micrometer sized samples of molecular hydrogen, trying to turn it into a superconducting metal. They have reported darkening of the sample (ref. 16), indicating absorption of light, but further work is needed to determine if it is a partially conducting form of molecular hydrogen or the desired metallic atomic hydrogen. Their darkened sample returned to its normal state when the pressure was released. Similar work, sponsored by the AF Astronautics Laboratory, is also underway by Isaac Silvera at Harvard.

Even if metallic hydrogen can be formed at high pressure, no one knows what will happen when the pressure is released. Some theorists predict it will be metastable, and stay in the dense metallic form. (Diamond is a metastable form of graphite formed at high pressure but stable at low pressure.) Other theorists predict it will rapidly revert to the molecular form of hydrogen. If it remains stable at some pressure substantially less than that necessary for form it, there is a lot of engineering to be done to move from micrometer sized batches to continuous flow production of tons per day, but with a specific impulse of 1700 seconds, metallic hydrogen will do everything for space travel that beamed laser power, nuclear thermal, and antimatter rockets could do, and be a lot cheaper and safer.

Magnetic Engines and Nozzles

Nearly all advanced high thrust, high specific impulse rocket concepts that use high power electromagnetic thrustors, metallic hydrogen or metastable helium fuels, beamed laser or microwave power, fission, fusion, or antimatter energy; in fact, any rocket technique that produces thermalized propellant exhausts with specific impulses above 1500 seconds, all have the same problem. The high energy exhaust from any of these processes will produce a blazing plasma that will melt the reaction chamber and nozzle if they are made out of ordinary refractory materials. One solution is to make the engine and nozzle out of magnetic fields. There are two ongoing experimental research efforts on magnetic nozzles to handle these high density, high temperature plasmas. One by Joel Sercel at Caltech sponsored by JPL, and one by Ted Yang and astronaut Franklin Chang-Diaz at MIT sponsored by JPL and AFOSR. Some recent studies (ref. 17), however, have uncovered a potential problem. Plasma constrained to an axially symmetric flow by an axially symmetric magnetic field will experience a resistive drag as it tries to axially detach itself from the radially diverging magnetic field lines. This drag will be transmitted to the vehicle through the magnetic field coils. Research in the area of magnetic field assisted reaction chambers and exhaust nozzles needs to be continued and expanded. Otherwise, we may find that we have developed a new propulsion energy concept without having the means to convert that propulsion energy into propulsive thrust.

LIVING WITHOUT ROCKETS AND LIKING IT

If in the next few years space nuclear propulsion proves to be politically unpalatable, and the HEDM programs do not produce a new chemical fuel with a significant increase in specific impulse over liquid-oxygen/liquid-hydrogen, then those in charge of the future of this nation's space programs are going to face a harsh reality. Our future in space can only be assured if we give up our dependence on self-contained rockets. A rocket not only has to carry its payload, but it must also carry its engine, its energy source, and its reaction mass. If we want rapid, economical space travel within the solar system, we must develop and demonstrate new technologies that are not rockets and are not limited by the exponential mass growth of the rocket equation. Fortunately, there are plenty of candidates. Some examples are: beamed power laser propulsion, solar thermal propulsion, solar sails, magnetic sails, and tethers. Some do not carry their engine, some do not carry their energy source, some do not carry their reaction mass, and some do without all three.

LASER THERMAL PROPULSION

Beamed power laser propulsion received a big boost in the past few years. Since 1987, SDIO has sponsored a two million dollar per year research program on laser propulsion managed through Lawrence Livermore National Laboratory (LLNL). Most of the effort has focussed on the nozzle-less planar thruster originally suggested by Arthur Kantrowitz (ref. 18). The payload sits on a solid block of ablative propellant such as plastic or water ice (see Fig. 2). An "evaporation" laser pulse ablates a few-micrometer-thick layer of propellant, forming a thin layer of gas. A second laser pulse then "explodes" this gas layer, producing thrust on the plate of propellant. The process takes a few microseconds and is repeated at 100-1000 Hz rates. An important feature is that the explosive expansion takes place so close to the plate of propellant that no nozzle is needed. The resultant thrust is normal to the plate and independent of the direction of the incident laser light, allowing the vehicle to fly at an angle to the laser beam. The vehicle can therefore transition into a near-circular orbit without requiring an apogee kick motor. The vehicle is steered from the ground by moving the laser beam off the center of the base plate, and so does not need an onboard guidance system. The payload size depends on the laser power; 20 MW can launch a 150 kg vehicle carrying a 20 kg payload. Higher powers can launch proportionately larger payloads. Peak accelerations are comparable to those of chemical rockets.

Jordin Kare of LLNL (ref. 19) reports that experiments have now been conducted at several industry and government laboratories. The double-pulse thruster concept works, producing high thrust efficiency and specific impulses up to 800 seconds. The actual thrust efficiencies obtained to date are only about 10%. The LLNL-SDIO program had hoped to use the induction linac fee electron laser (FEL) proposed by LLNL for SDIO tests at White Sands to do high-power suborbital (and possibly orbital) launch tests. SDIO has now decided to build a lower power RF-linac FEL, which puts out a poor pulse format for pulsed laser propulsion.

Another approach to laser propulsion is to absorb laser light in a plasma "flame" sustained by laser light focused in the center of a flowing stream of propellant gas. Thrust levels as high as 10,000 N with specific impulses of 1000 seconds appear achievable using hydrogen as the propellant gas. Dennis Keefer and others of University of Tennessee, working with a 1 kW CW CO_2 laser, have reported an absorption efficiency of 86% and a thermal efficiency of 38% in an argon plasma at 2.5 atm. They repeated the experiments using an RF-linac free-electron-laser that produces a 0.1 ms burst of 10 ps pulses separated by 46 ns. These short pulses ignited the argon gas and formed a plasma that absorbed 92% of the laser power (ref. 20). Hydrogen and nitrogen gas did not ignite at the pulsed laser powers available.

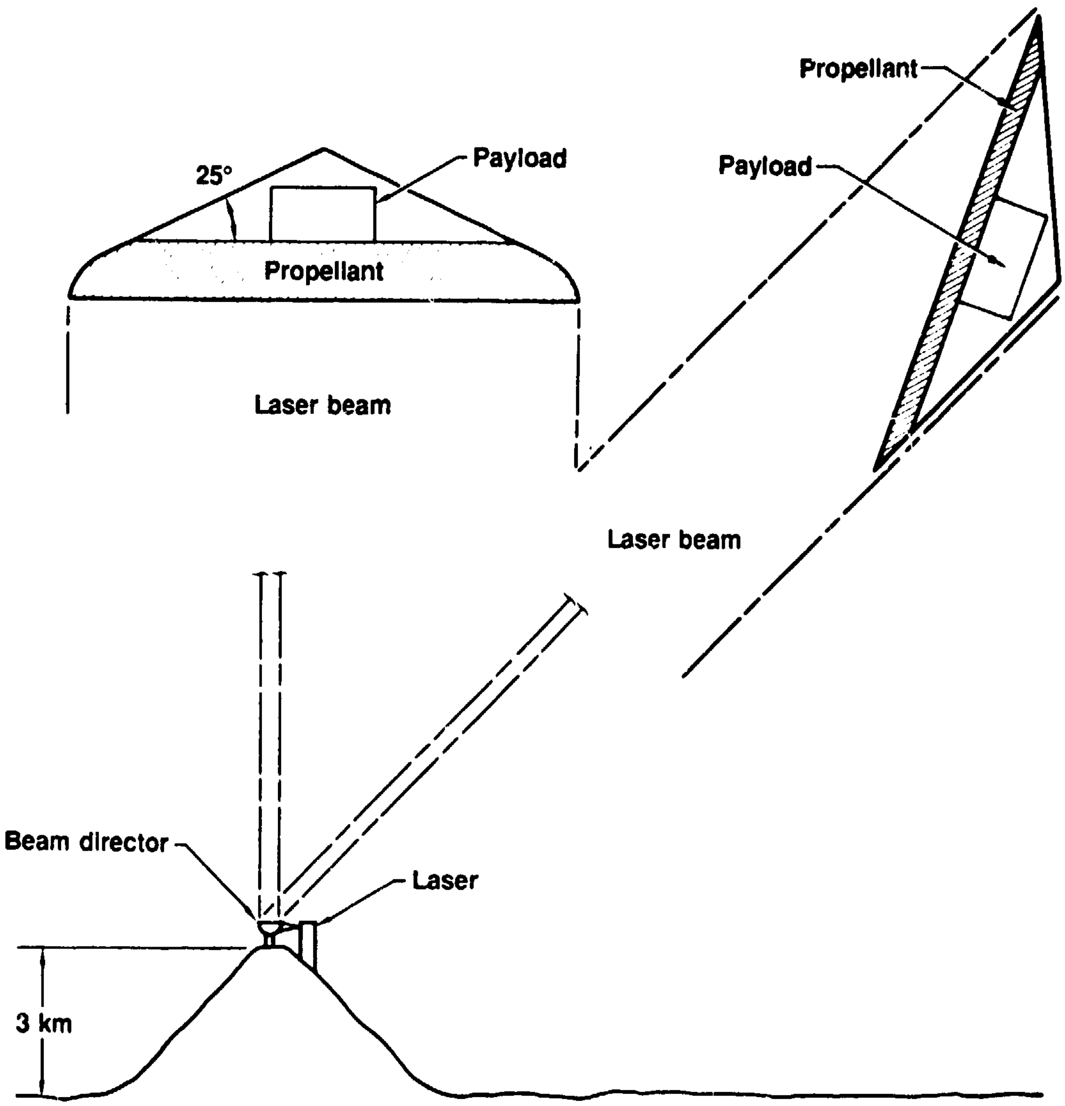

Fig. 2 - Schematic of Generic Flat Plate Laser Rocket

Herman Krier and Jyotirmoy Mazumder of University of Illinois at Urbana-Champaign have recently achieved a very promising 81% absorption efficiency and a 72% thermal efficiency with 7 kW of CO_2 laser power into a 2.5 atm hydrogen plasma flowing at 10.3 m/s. Leik Myrabo of Rensselaer Polytech (ref. 21) is investigating a 300 kg launch mass Lightcraft Technology Demonstrator that rides up a laser beam from a 100 MW-class ground-based free-electron-laser. The laser power heats scooped air in the atmosphere and onboard propellant in space, pushing the 124 kg spacecraft into orbit.

Laser powers as low as 1 MW would useful for LEO-GEO orbit raising without relay optics. 10-100 MW lasers can launch small payloads from the ground. With up to 100 launches a day, a 20 MW, 20 kg payload launcher could place several hundred tons in orbit per year. Low gigawatt lasers could launch multiton spacecraft with the same ease that present multigigawatt chemical rockets do. Laser rockets will have better payload fractions since the heavy power plant is left on the ground and the higher specific impulse results in lower propellant fractions. Although gigawatt lasers are not off-the-shelf items, there is no doubt they could be built if the need was strong enough.

SOLAR THERMAL PROPULSION

One method of obtaining power and propulsion in space is to use large inflated concentrating mirrors to gather and focus solar energy onto a light-absorber which converts the solar energy into thermal energy. The thermal energy can be used to operate a heat engine to produce electricity, or it can be used to heat propellant (typically hydrogen) which can then exhausted to produce thrust. The major effort in this area is being sponsored by the Air Force Astronautics Laboratory (AFAL). Their program (ref.22) has proceeded through the research phase and is now directed toward flight tests in the late 1990s. In the mid 1980s, Rocketdyne built a small thrustor for AFAL consisting of a cylindrical cavity lined with rhenium tubing through which flowed hydrogen gas. Sunlight focused into the cavity from a 25 kW solar facility at AFAL produced 4.45 N of thrust at a measured specific impulse of 820 seconds.

AFAL is now investigating two advanced forms of thrustors. One uses a porous disk heat exchanger with a series of stacked discs of varying optical absorptance but constant hydrogen flow rate. The other is a directly heated gas concept where, similar to the CW laser propulsion experiments, the solar energy is absorbed in a solar sustained plasma "flame" in a flowing gas.

In the mid-1980s, L'Garde constructed a three meter on-axis diameter demonstration model inflatable concentrator for AFAL. The measured concentration ratio was a very respectable 12,000:1. More recently, a 4 by 6 m off-axis inflatable reflector was manufactured with a concentration ratio of 10,000:1. New fabrication approaches seem to indicate that full-sized, off-axis 30 m diameter concentrators are in hand. The design goals for the Astronautics Laboratory orbital transfer solar thermal propulsion system are: two mirrors of 30 m projected diameter delivering 1.5 MW of thermal power at a concentration ratio of 10,000:1 and two thrustors operating at a specific impulse of 900 seconds and 222.5 N thrust (445 N total).

SOLAR SAILS

Solar sails are large, lightweight reflectors attached to a spacecraft that use light pressure from solar photons to obtain thrust. By tilting the sail to change the force direction, the light pressure can be used to increase the orbital speed of the spacecraft, sending it outward from the Sun, or decrease its orbital speed, allowing it to fall inward toward the Sun. Although the thrust available from sunlight is small (9 N/km^2), the solar sail never runs out of fuel. Over a long enough time, the small thrust can build up into extremely high $\triangle$Vs, allowing solar sails to take on missions that cannot be done by vehicles limited by the exponential growth of the rocket equation. A solar sail is ideal for shuttling of interplanetary cargo, since no refueling is required. Because the acceleration levels increase dramatically as the sail gets closer to the Sun, the solar sail exhibits tremendous performance for Mercury or Solar Probes, and many missions to the outer planets often benefit from an initial inward trajectory. (This was particularly true for the rendezvous mission to Halley's comet in its retrograde orbit.) Another ideal mission for a solar sail is a multiple small body rendezvous mission to the asteroid belt. Solar sail "tugs" can then be sent out to drag the more promising asteroids into an Earth or Mars orbit. Once the "pipeline" from the asteroid belt is full, the long transit time of solar sails hauling large cargos becomes academic.

In 1976-77, JPL carried out detailed engineering studies (ref. 23) on a square sail and a 12 blade "heliogyro" sail designed to rendezvous with Halley's Comet, not just fly by at high relative speed. The solar sail lost to solar electric propulsion, which in turn lost to the budget cutters. Solar sail studies were kept alive in the 1980s by Robert Staehle and a volunteer group of Los Angeles area engineers. They formed the World Space Foundation, which built the first solar sail in 1981. This "brassboard" model was deployed on the ground in order to confirm the packaging and deployment configuration. They presently have an engineering development model in design prototype form and are looking for a piggyback launch in order to verify the deployment procedure and fly a test mission to the Moon.

In 1989 the Columbus 500 Space Sail Cup race was announced. The purpose is to launch three or more solar sails into high earth orbit where they will undertake to travel to the Moon, and perhaps to Mars. The three lead vessels, named after the Nina, Pinta and Santa Maria, will come from three continents. One from Europe--the origin of Columbus's voyage, one from the Americas--the land Columbus discovered, and one from Asia--the land Columbus tried to reach and thought to have found. The lead ship selected for the Americas entry is the Johns Hopkins University Applied Physics Laboratory "Sunflower", a circular solar sail held in a flat circle by a large hoop supported by guy wires from a central mast. The sail has a diameter of 170 m and total mass of 180 kg. The sail is composed of 480 triangular pieces of reflective foil arranged like the petals of a flower. Some petals twist about their long axis to provide roll torque. No long seams are used, making it easy to manufacture, and each petal is individually unrolled by small deployment springs. Although the Columbus 500 Space Sail Cup Committee still has not obtained the funding required, the project is continuing ahead.

Solar Photon Thrustor

In 1988, a new type of solar sail called a "solar photon thrustor" (ref. 24) was invented (it was later found to have been first described by A.P. Skoptsiv of the USSR in 1971). The new sail concept is based on the realization that a space vehicle that uses a solar sail for propulsion can be significantly improved in performance by separating the function of collecting the solar photons from the function of reflecting the solar photons (see Fig. 3).

In the Solar Photon Thrustor concept, the collector is a large reflecting surface similar in size and mass per unit area to that of a standard flat solar sail. The collector faces the Sun so as to always present the maximum area for collection of sunlight. The collector is modified in structure so it is a light concentrator. The concentrated sunlight is directed to a reflecting surface of much smaller mass, which redirects the light to provide net solar photon thrust in the desired direction. Note that by tilting the reflecting mirror, the sunlight can be reflected in any desired angle off the axis formed by the Sun-spacecraft line, while rotation of the whole spacecraft around the Sun-spacecraft line allows direction of the reflected sunlight in azimuth around the Sun-spacecraft line. To minimize undesired torques, the collecting and reflecting portions of the system can be arranged so that the net force passes through the center of mass of the total system including payload.

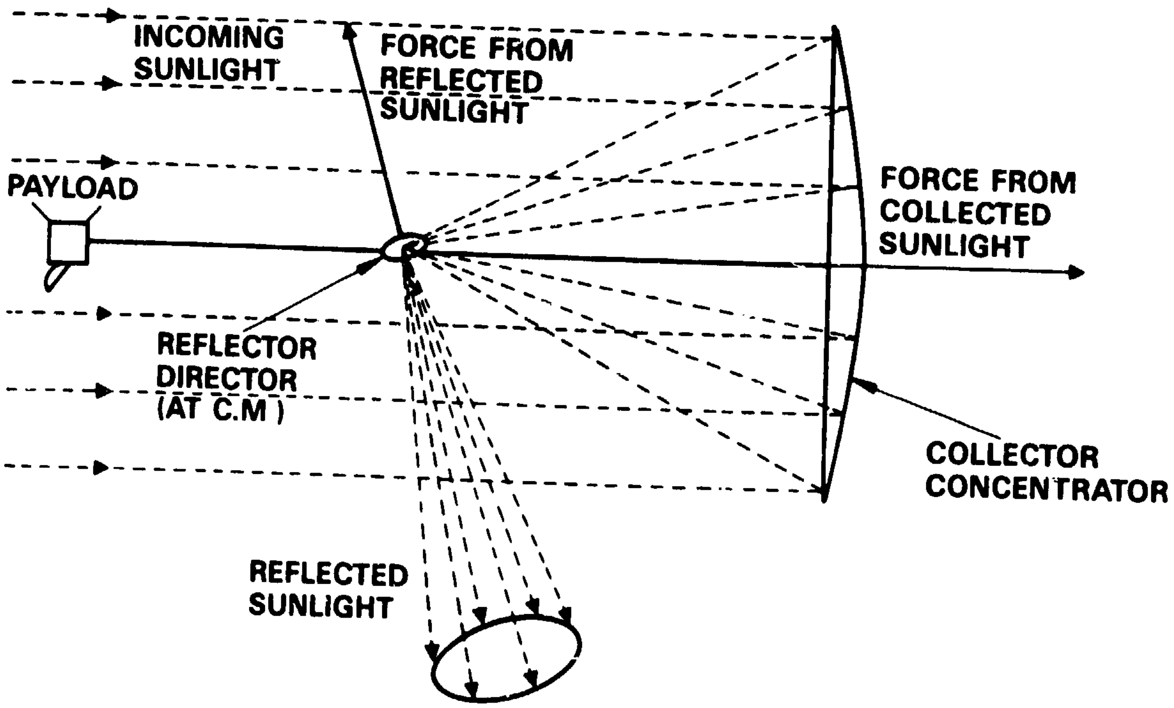

Fig. 3 - Schematic of Generic Solar Photon Thrustor

Since the collector of the sunlight in the Solar Photon Thrustor is always facing the Sun no matter what the desired direction of thrust, the Solar Photon Thrustor always operates in a maximum solar light power collection mode. This is in contrast to a flat solar sail propulsion system where the collector and reflector are the same sheet of reflecting material. In a flat solar sail propulsion system, if the desired direction of thrust is not directly away from the Sun, the sail must be tilted at some angle Θ with respect to the Sun-sail line. Since the sail is tilted toward the Sun, the effective collecting area of the flat solar sail propulsion system is decreased by an amount proportional to sinΘ. This means that the Solar Photon Thrustor always collects more solar light power and therefore provides higher total solar photon radiation pressure force for the same area of collector. Since the mass of any optimized light pressure propulsion system is dominated by the mass of the light collecting area, that means that a Solar Photon Thrustor system will have better performance in terms of maximum payload capability, maximum propulsive thrust, and minimum mission time than flat solar sail propulsion systems. High solar power concentration numbers are not needed for the Solar Photon Thrustor. A concentration ratio of only 100:1 means that the area (and therefore the mass) of the reflecting optics will be 1% of the area (and mass) of the collecting optics and therefore a negligible portion of the total spacecraft mass.

The electromagnetic radiation does not have to stay in its original form. For example, the collector could collect sunlight and concentrate it on a solar cell or thermal boiler electrical generation system. The electricity generated could be used to make microwave, laser, or other useful coherent radiation, which would be beamed down to Earth. The waste heat from the process would be radiated away into space. Both the beamed coherent power and the radiated waste heat would produce propulsive force of comparable magnitude to the collected light. With proper system design, the beamed power and waste heat, along with the collected light, could provide all the propulsion needed.

Richard Moss, M.D. of Plymouth, Massachusetts has found (ref. 25) that a solar photon thrustor can be launched at shuttle altitudes. (Standard sails can only operate above 1000 km altitude, where the light pressure force exceeds the atmospheric drag.) If the solar photon thrustor is launched into a Sun-synchronous orbit over the terminator, the large collector sail facing the Sun will have minimum drag since it is flying edge-on to the residual atmosphere. It only takes four days to go from Shuttle altitudes to a safe 1000 km drag-free altitude.

Solar Sails for Manned Missions to Mars

John Garvey of McDonnell-Douglas has been reexamining the use of solar sails for the manned exploration of Mars initiative. Prior studies by Carl Sauer of JPL resulted in optimized trip times of 824.5 days (2.25 years) for an Earth to Mars transfer. Garvey realized that most of that time was spent spiraling up from LEO to escape, matching velocities with Mars with a sail tilt angle that was almost edge-on to the Sun, and spiraling down from escape to LMO. By using a mixture of chemical boost on departure, solar sail propulsion during transfer, and aerobraking upon arrival, Garvey has found non-optimized mission profiles of 150 days one way, with even shorter return trip times for the empty sail. These short mission times cut the crew consumable weight drastically and eliminate the need for artificial gravity.

Garvey has also found a way to deploy a solar sail at Space Station altitudes, where astronauts can help solve deployment problems. The deployment is carried out at the end of a 100 km long upward-going tether, with the sail kept edge-on to the orbital motion to minimize drag. When the sail is released, it will rise upward in an elliptical orbit to where it can turn to the Sun and fly into space on its own power.

Exotic Orbits With Solar Sails

If a solar sail is made light enough, it can "hover" without orbiting--the light pressure from the solar photons balancing the gravity attraction of the Sun (and/or Earth). Colin McInnes of the University of Glasgow recently found (ref. 26) a large family of solar sail orbits around the Sun that produce nearly any desired orbital period (for example: zero--hovering anywhere over the Sun, moving heliosynchronously with features on the solar surface, or matching the orbital period of a planet) at nearly any desired orbital distance, in or out of the ecliptic plane. The light pressure from the Sun modifies the orbital equations so much that the orbital period is nearly independent of the orbital radius. For another example, James Early of Lawrence Livermore National Labs describes in reference 27 a large solar sail maintaining station between the Sun and the L2 point of the Earth. If the sail were 2000 km in diameter (made of lunar material), it would block enough sunlight (2%) to provide a technological solution to the greenhouse warming problem.

Robert Forward of Forward Unlimited has discovered (ref. 28) light-levitated geosynchronous orbits around the Earth that are at equilibrium positions north or south of the presently crowded equatorial geostationary orbit. The orbital radii of these light-levitated orbits are slightly less than the geostationary orbit radius, the center of the orbit is north (or south) of the center of the Earth, but the orbital rotation rate of the spacecraft matches that of the Earth's surface. Forward has also invented (ref. 29) a new kind of spacecraft that uses solar sails to assume non-orbiting equilibrium "polesitter" positions that allow communication, broadcast, or weather spacecraft to continuously hover over the polar regions of the Earth (or any other planet in the solar system). Since these spacecraft do not orbit, and therefore are not "satellites" of the Earth, the generic term of "statite" has been coined for them. Forward Unlimited has filed worldwide patents on the statite concept and is presently gathering private funding in order to fly a demonstration model.

To properly appreciate the statite concept, it is important to realize that all of the thousands of space objects presently in orbit around the Earth use the centrifugal force generated by their orbital motion to balance the Earth's gravitational force. By contrast, the statite is a space object that does not use centrifugal force from orbital motion about the Earth to counteract any significant portion of the Earth's gravitational force. Instead, the statite uses a solar sail propulsion system to maintain the statite and its payload in a desired fixed position adjacent to the Earth by balancing light pressure force against the Earth's gravitation force.

As shown in Figure 4, a space vehicle containing a Earth-services payload (broadcast, communications, weather, navigation, etc.) is attached to a solar light pressure propulsion system to form a space services station. After launch to an altitude where the light pressure propulsion system can function, the light pressure propulsion system is used to transfer the station to a point above the north or south hemisphere of the Earth where the gravitational pull of the Earth is counterbalanced by the light pressure force from the Sun.

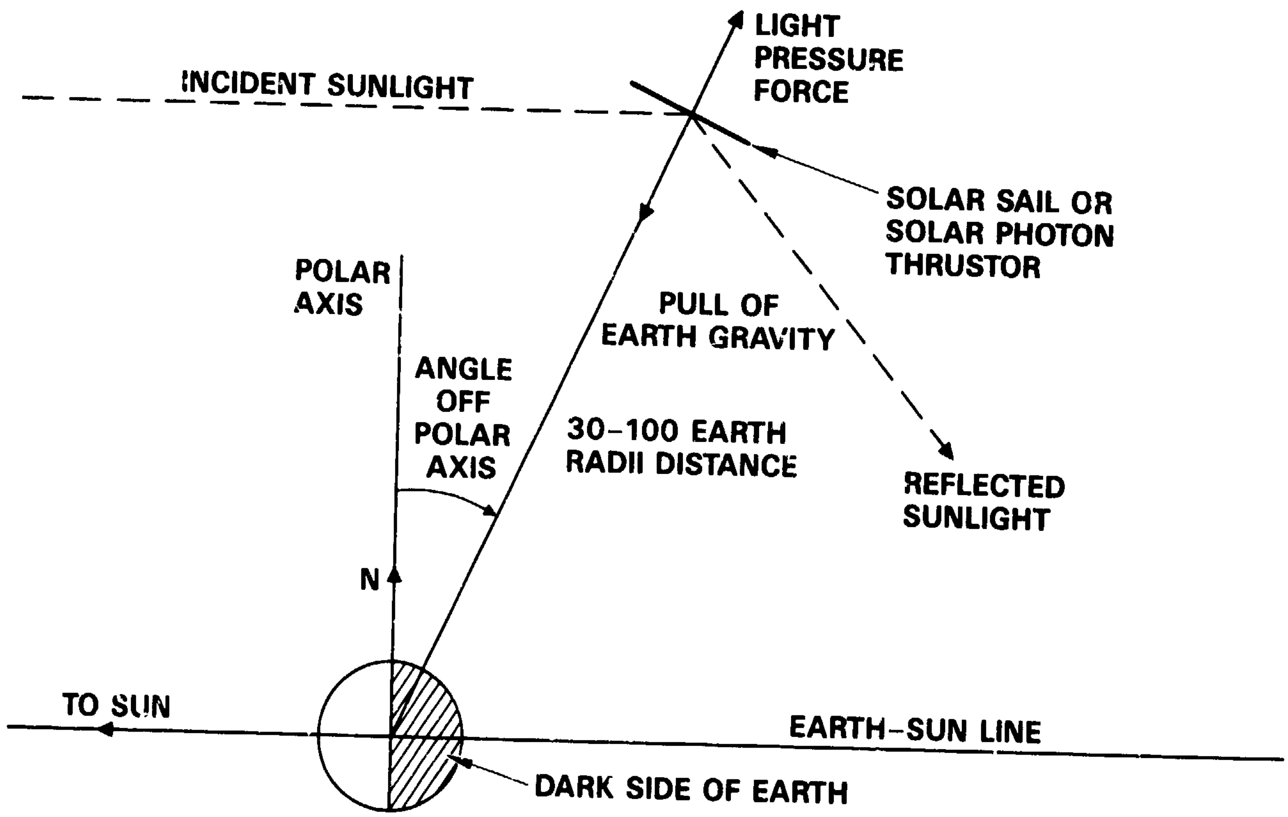

Fig. 4 - Schematic of Generic Statite Concept

In most versions of the system, the statite is offset from the polar axis. The statite stays fixed at a point above the dark side of the Earth, while the Earth spins beneath it. The statite does not have to be positioned directly opposite from the Sun. It can be placed anywhere over a large area on the dark side of the Earth. This is in contrast to the single linear arc of the equatorial geostationary orbit. From the viewpoint of an observer on the rotating Earth, this version of the statite rotates around the pole once every 24 hours (a solar day). Thu , ground stations for communication with these statites must have their antennas on a polar mount with a 24 hour clock drive. Since the distance between the ground station and the statite does not change significant'y and the doppler shifts are very low, the electronics needed for these versions of the system are nearly as simple as those at the fixed position ground stations. There is an alternate version of the statite system where the statite is kept directly over the North or South Pole of the spinning Earth. To an observer on the Earth, the statite stays fixed above the pole while the stars rotate around it. In these versions, the ground stations can used fixed mounted antennas and simple fixed gain, fixed frequency electronics.

A typical distance of a statite from the center of the Earth is 30 to 100 Earth radii. The better the performance of the sail, the closer the balance point. (For reference, geostationary orbit is at 6.6 Earth radii and the Moon is at 63 Earth radii.) The round-trip delay time for 100 Earth radii is 4 seconds, making the statite more suitable for direct broadcast, fax, data, and weather services than two-way telephone conversations. The advantages of the statite concept are: it provides continuous service to a region using a single spacecraft without requiring a slot on the already crowded equatorial geostationary orbit, and it provides continuous coverage to regions of the Earth that are too close to the poles to use equatorial geostationary orbit satellites. The disadvantages of the statite concept are: constant control is required to maintain station, the round-trip link time is in seconds, and in most versions the ground station antenna must rotate once a day.

MAGNETIC SAILS

Magnetic sails or "magsails" are a derivative form of solar sails that use a completely different type of physical interaction with the Sun than solar light pressure sails (ref. 30). Invented by Dana Andrews of Boeing Aerospace and Robert Zubrin of Martin-Marietta Denver, a magsail is a simple loop of high-temperature superconducting wire carrying a persistent current. The charged particles in the solar wind are deflected by the magnetic field, producing thrust. Although the thrust density in the solar ion wind flux is five thousand times less than the thrust density in the solar photon flux, the mass of a solar sail goes directly as the area, while the mass of the magsail goes as the perimeter of the area enclosed. In addition, the effective cross-sectional area of the magnetic fields around the magsail is about a hundred times the physical area of the loop. As a result, preliminary calculations show the thrust-to-weight of a magsail can be an order of magnitude better than a solar sail. Recent analyses indicate that a properly sun-shielded cable can be passively maintained at a temperature of 65 K in space, well below the superconducting transition point for many of the new high-temperature superconductors.

TETHERS

Tether propulsion a technology that will fly soon. NASA is funding Martin Marietta to build the tether (2.5 mm diameter and 100 km long) and deployment mechanism, while Italy is building the spacecraft that will fly at the end of the tether. The first experiment, scheduled for 1991, will deploy the spacecraft upward from the Shuttle on a conducting tether cable to demonstrate power generation from the motion of the conducting cable through the Earth's magnetic field. By pumping current through the cable, thrust would be generated by the "push" of the cable against the Earth's magnetic field. The second flight will deploy an atmospheric research spacecraft downward, where it will fly through the upper atmosphere, too low for spacecraft and too high for aircraft. The tether connection to the Shuttle spacecraft provides the propulsion needed to overcome the drag. Ivan Bekey, formerly at NASA Headquarters and now on the National Space Council, has been championing the use of tethers for many space applications (ref. 31 and 32), including throwing payloads from LEO to GEO, electromagnetic propulsion using a conductive tether, and momentum transfer through the Space Station. In the latter application, an Orbital Transfer Vehicle is launched from an upward going tether at the same time as the Space Shuttle deorbits from a down-going tether, all without using any fuel. The Space Station is unaffected--it merely transfers energy and momentum between the two vehicles. Paul Penzo of JPL has shown (ref. 33) it is possible to use tethers to move payloads from planetary body to planetary body (see Fig. 5), such as low Martian orbit to low Earth orbit.

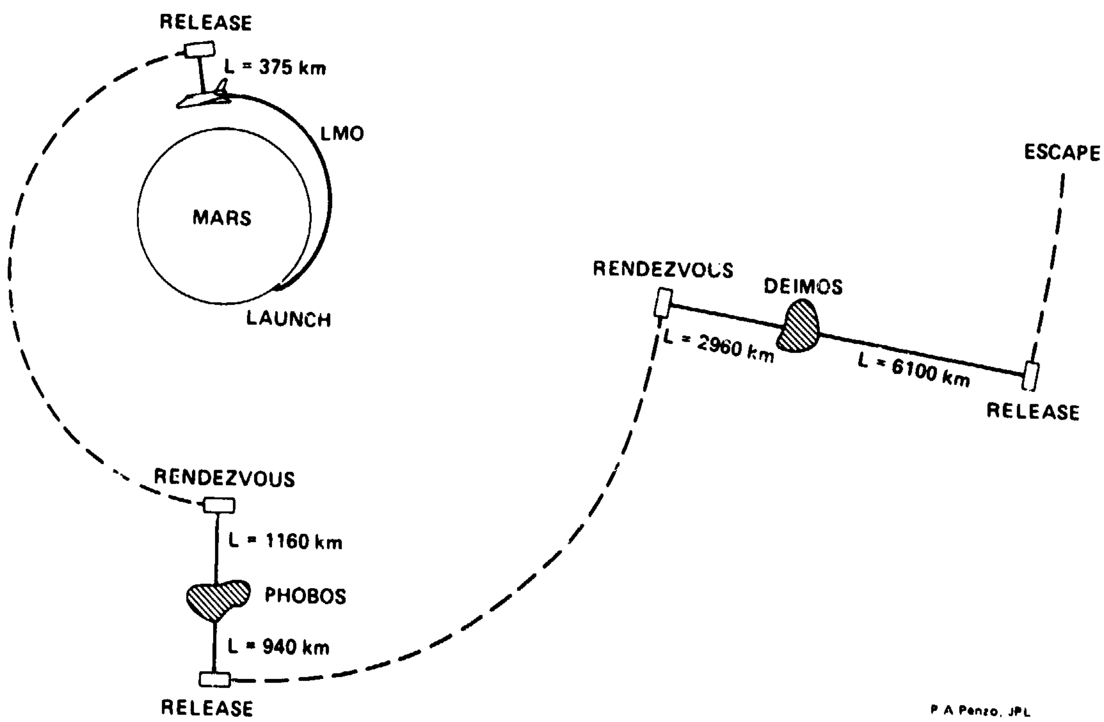

Fig. 5 - Schematic of Generic Mars Tether Transport System

Hans Moravec of CMU has shown in reference 34 that a long rotating Kevlar tether in orbit around the moon or small airless planet (like the Moon or Mars) can touch down to the surface six times an orbit, simultaneously dropping off and lifting up payloads weighing a reasonable fraction of the tether mass. This concept is being reevaluated by Joseph Carroll of Tether Applications for its potential impact on the Lunar Base initiative. Using the tether material Spectra, which has improved properties over the more familiar Kevlar material, Carroll has done a preliminary design on an ambitious tether transport node facility designed to provide a 1 km/s ΔV to 10 ton payloads. To stay in orbit, a typical facility mass should be at least 300 tons for 10 ton payloads, but the 300 km long tether itself would only mass 7 tons. One tether facility would be placed in a circular 400 km orbit and another in a highly elliptical orbit with a 4:1 period resonance. As shown in Figure 6, payloads would be picked up from a 150 km or lower earth orbit by the lower facility and tossed into an intermediate elliptical orbit with an orbital period twice the lower facility and half the upper facility. There the payloads would be picked up by the higher facility and tossed to the Moon. At the Moon, the payloads would be retrieved by a 200 ton, 1160 km diameter rotating tether and deposited on the surface of the Moon. By arranging things so an equal amount of mass flows in both directions, this system is self-powered. Bags of lunar dirt flowing down the tether system into the deep Earth gravity well will be the "fuel" needed to move payloads from LEO to the surface of the Moon.

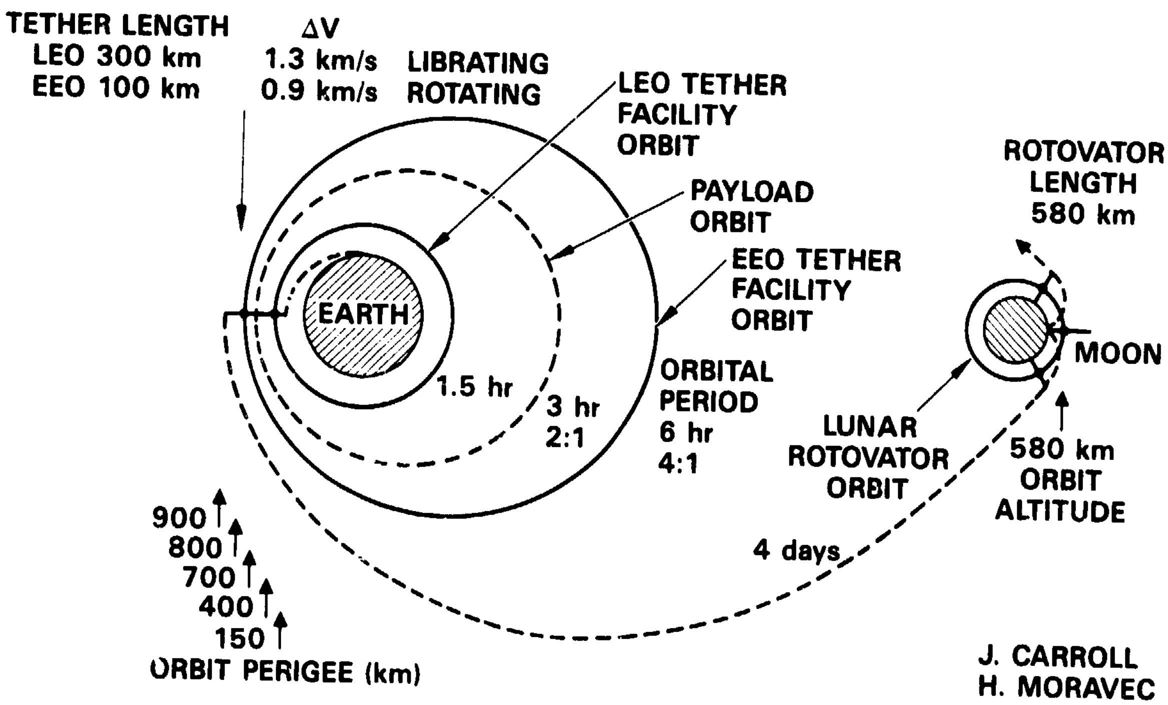

Fig. 6 - Schematic of Generic LEO-Lunar Surface Tether Transport System

Tether "Bootstrap" Propulsion
Geoffrey Landis at NASA/Lewis has shown in reference 35, how a spacecraft starting in a low circular orbit about Earth can use a power supply and a long tether "pushing" against the Earth's gravity gradient field to "bootstrap" itself (and the tether) up the gravity well nearly to escape in less than a month without using propellant. The basic concept is based on the fact that if two halves of a spacecraft (or a spacecraft and its expended booster) are extended on a long tether, the center-of-mass of the extended system shifts slightly downward from the original center-of-mass and the orbital period decreases. This shift in the center-of-mass occurs because the Earth's gravity force causes an acceleration on the masses that varies as $1/r^2$, while the counteracting centrifugal force due to orbital motion causes an acceleration that varies as r. For very long tethers, the two forces no longer exactly cancel at the two ends and there is a residual, second order, force which must be balanced by a shift in the center of mass. When the tether is pulled in again, the center-of-mass of the combined system raises upward.

As shown in Figure 7, by alternately extending and contracting the tether at proper points in the orbit, the tether can be used to "pump" an initially circular orbit into a highly elliptical orbit. Theoretically, if the initial orbit is circular and at an altitude of greater than one earth radii (orbital radius of greater than two earth radii or greater than 13,000 km), then the final orbit can be an escape parabola. Note that the angular momentum of the initial and final orbits are the same, so no angular momentum needs to be supplied. The energy of the escape parabola is much greater than the energy of the initial circular orbit, so energy needs to be supplied, either from an onboard power supply or by collecting externally supplied power. The final configuration has the payload, tether, and counterweight flying off away from the Earth at some residual velocity, so it has some linear momentum. To conserve linear momentum, the tether has transferred linear momentum to the Earth by coupling to the gravity tidal fields of the Earth through its extended length. Although it looks like the system is "pulling itself up by its bootstraps", it is not. In effect, the tether is "climbing" out of the Earth's gravity well by coupling to the nonlinearities in the gravitational gradient fields or gravity tides.

Unlike other tether propulsion concepts in the literature, where one mass (the payload) is raised in orbit while another mass (the counterweight) is lowered in orbit, the technique developed by Landis allows the center-of-mass of the entire system to be raised from a low circular orbit into a high elliptical orbit--conceptually into an escape orbit from Earth--without the use of rockets or reaction mass. Energy is required, which can be supplied from an onboard power supply, but no reaction mass is needed, and if the Earth-to-LEO booster is used as a counterweight for the payload mass, the only weight penalty is the mass of the tether (compared with the weight penalty of a LEO-GEO booster rocket).

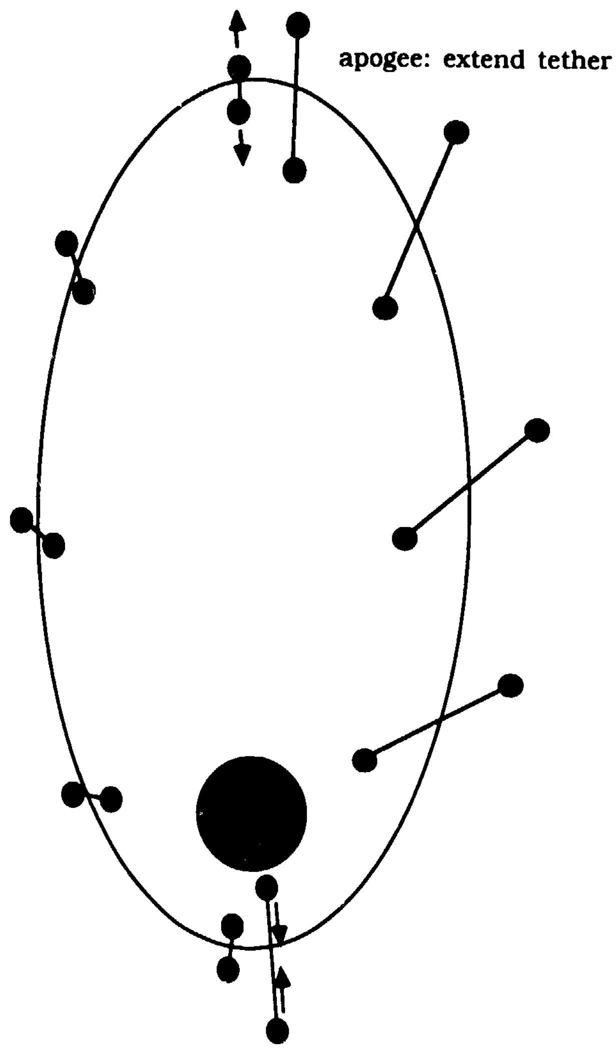

Fig. 7 - Schematic of Generic Tether "Bootstrap" Propulsion Concept

Cable Catapult

A cable catapult is a new type of propulsion system proposed by Forward that uses a long tether as a launch rail (ref. 36). As shown in Figure 8, the tether cable is pointed in the desired direction of travel. A payload is attached to a linear motor capable of traveling along the cable. The linear motor accelerates along the cable until the payload reaches the desired launch velocity, at which point the payload is released. The linear motor then decelerates to a halt to await the arrival of an incoming payload.

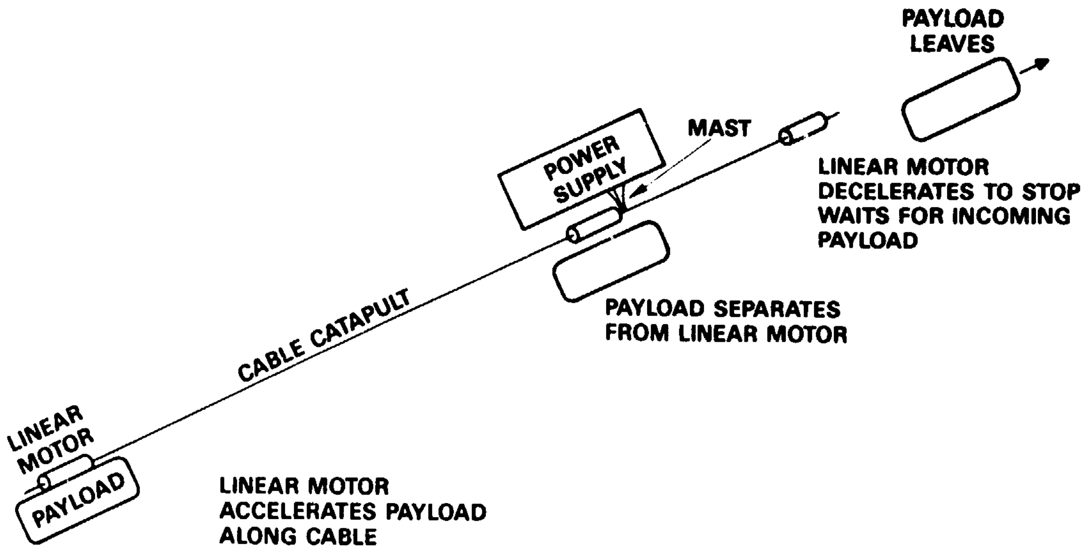

Fig. 8 - Schematic of Generic Cable Catapult Concept

In the past, tethers have been considered for transporting payloads to and from the Moon, Mars, and other bodies in the solar system. These tether propulsion systems usually involved swinging or rotating tethers. Moravec has shown that the maximum tip speed V of a rotating tether (and therefore the maximum speed at which a rotating tether can launch a payload) is a function of the "characteristic velocity" of the cable given by the square root of the ratio of the design tensile strength T to the density d of the material in the tether or $v=(T/d)^{1/2}$ and the ratio of the mass M of the tether to the mass m of the payload. The exact expression is:

$$\frac{M}{m} = (2\pi)^{1/2} \frac{V}{v} e^{V^2/2v^2} \operatorname{erf}(V/2v)$$

where erf is the error function (typically of order unity or less). This can be compared to the ratio of the rocket mass to the payload mass of a rocket where v is the "exhaust velocity" of the fuel.

$$\frac{M}{m} = e^{V/v} - 1$$

Which is exponential in V/v, while the rotating cable mass ratio is exponential in the square of V/v. In contrast, Forward has shown in reference 36, that the ratio of the tether mass to the payload mass used in the cable catapult mode varies as:

$$\frac{M}{m} = V^2/2v^2 \quad .$$

Because of the squared exponential growth of the mass of the tether in a rotating tether system, the maximum launch velocity attainable for practical launcher to payload mass ratios is three times the characteristic velocity of the cable material or 3 km/s for a 1 km/s Kevlar cable. A cable catapult using the same amount of cable material could give the payload a launch velocity of 30 times the cable characteristic velocity or 30 km/s. Improved cable materials having higher characteristic velocities will allow interplanetary travel at 30-100 km/s. This could shorten trip times to Mars from years to months.

FAR FUTURE PROPULSION

Even more exotic propulsion concepts abound in the literature. Many advanced nuclear propulsion concepts have been proposed that depend upon some exotic physical process being found practical. For one example, George Chapline of Lawrence Livermore National Lab has proposed a fission fragment rocket using thousands of kilometers of americium coated fibers suspended on dozens of rotating 100-meter-sized wheels as a combination fuel source and heat radiator. Others have examined the propulsion applications of various potential techniques for catalyzed cold fusion, using palladium, muons, fractional charges, magnetic monopoles, and strange matter. None of these fusion techniques look promising for propulsion, primarily since in most cases the energy output is in the form of high energy neutrons, which are difficult to turn into thrust except through an indirect thermalization process.

We do not lack new ideas to explore: some examples are studies on laser and microwave pushed sails to the planets and stars (ref. 37 and 38), and extracting laser power from the mesospheres of Mars, Venus, and maybe Earth (ref. 4). Even further out are recent papers on negative matter propulsion (ref. 39), space warps (ref. 40), and serious-but-skeptical studies of Biefield-Brown field propulsion and electrogravity induction field theories (ref. 22).

SUMMARY POLEMIC

In this review I have discussed a number of exotic power and propulsion techniques, ranging from eminently feasible to the wildly impossible. But it is important for you, the reader, to realize that my main message is that we don't need to wait for truly exotic technologies like metallic hydrogen, antimatter, or space warps to improve the nation's space propulsion capabilities by orders of magnitude increase in performance and orders of magnitude decrease in cost. Chemical rocket propulsion is fine when the $\triangle V$ is small, but for the more ambitious missions, this nation needs to put substantial development funds into making real those advanced space propulsion technologies that have already shown their potential value in decade after decade of paper studies.

Solar and nuclear electric propulsion should come first, not small systems for secondary tasks like North-South station keeping or Space Station drag makeup, but large megawatt and multimegawatt primary propulsion systems for OTV tugs, Earth-Lunar shuttles, and manned missions to Mars. Then solar sails, first for communication, broadcast, and especially weather satellites that are not limited to the equatorial geostationary orbital arc, second for scientific monitoring stations hovering over the Sun, planets, and moons of the solar system, and third for hauling cargo to and from Earth, the planets, and the asteroid belt--without the expenditure of fuel.

Next should come rotovators made of long rotating Kevlar tethers that will allow transport of massive quantities of material to and from low orbit to the surface of planetary bodies such as the Moon, Mars, Mercury, and most of the moons in the solar system--again without the use of fuel. Rotating tethers around the Earth could also move massive amounts of material from LEO to GEO or escape--using no fuel in the process as long as the amount of material being brought down the gravity well of Earth exceeds the amount being hauled up.

To get off the Earth and into LEO, we must either bite the political bullet and push high-thrust hot hydrogen exhaust nuclear thermal rockets with their radiation hazard, or stick with chemical rockets and their greenhouse hazard. High thrust laser propulsion, either pulsed or CW, is an alternate choice with its own set of operational and environmental problems that need engineering demonstration, not another mile-high stack of paper studies.

Mission planners must use what they know works in order to plan a mission. If future missions, such as a return to the Moon, or the manned exploration of Mars, are to be made economically feasible, NASA needs to stop the interminable paper studies and move into the development and demonstration of advanced forms of space propulsion such as nuclear, electric, lightsail, tether, and laser propulsion. That way, those mission planners will have some viable alternatives to work with. Otherwise, this nation is going nowhere in space.

ACKNOWLEDGEMENTS

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