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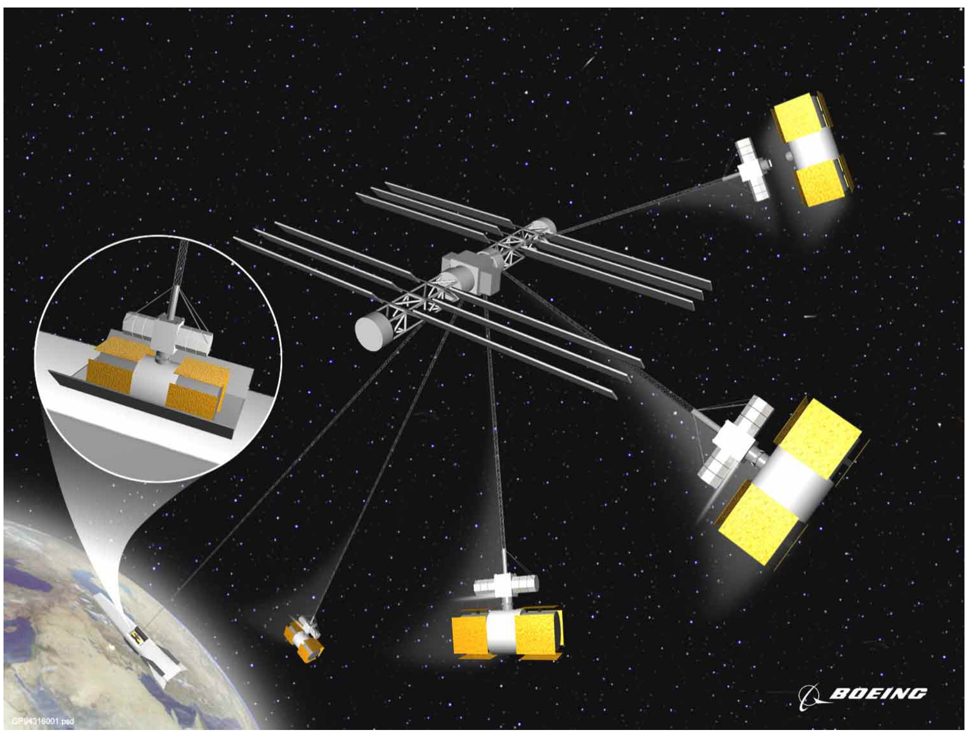

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ABSTRACT

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is a novel architecture for an Earth-to-orbit launch system consisting of: a completely reusable airbreathing subsonic-to-hypersonic dual-fuel airplane which transports the payload from the ground to some intermediate point in the upper atmosphere; an orbiting spinning space tether system which picks up the payload from the intermediate point and takes it on into orbit; and a grapple assembly for transferring the payload from the hypersonic airplane to the lower end of the space tether. The system is revolutionary in that it minimizes, and perhaps even eliminates, the use of rockets for Earth-to-orbit launch of satellite payloads and even passengers. For the hypersonic airplane portion of the HASTOL system we use an existing Boeing design for the DF-9, a dual-fuel airbreathing launcher that has benefited from over a million dollars in NASA/LaRC and Boeing funding during prior study efforts. The DF-9 has a 9 m (30 ft) long by 3 m (10 ft) diameter upward-opening central payload bay that can handle payloads up to 14 Mg (14 metric tons or 30,000 lb). With a full fuel load at takeoff, the hypersonic airplane masses approximately 20 times the payload mass, and can deliver the payload to 100 km (330 kft) altitude at an apogee speed of 3.6 km/s (12 kft/s) or approximately Mach 12. For the space tether portion of the HASTOL system, there are a number of design options, all of which will work, although some options promise better performance. The tethers can be built today using presently available commercial fibers. The tethers are long, typically 400 to 1600 km (1300 to 5300 kft) in length. The total mass of the space tether plus the Tether Central Station typically will be 30-200 times the payloads being handled. Most of that mass ratio requirement is driven by the fact that the tether system must mass considerably more than the payload it is handling, so that, upon pickup of the payload by the tether, the payload will not pull the space tether system down into the atmosphere. Thus, the advent in the future of better tether materials with higher strength at higher temperatures will not be used to lower the tether system mass significantly, but instead will be used to increase the tether safety margins, lifetime, and system performance, by allowing payload pickup at lower altitudes and lower speeds, thus decreasing the performance requirements on the hypersonic airplane portion of the system.

INTRODUCTION

The Boeing Company, Tethers Unlimited, Inc. (TUI), and the University of Maryland, have teamed to study the feasibility of a completely new concept for moving payloads and passengers from the surface of the Earth into low Earth orbit at low cost and low acceleration levels without the use of rockets as the main source of propulsion. Our joint study effort, funded by a $75,000 Phase I grant from the NASA Institute for Advanced Concepts, is halfway through its 6-month term. This paper builds upon work reported in a previous paper[1], and should be considered an interim report of the study results to date, rather than a finished piece of work.

HASTOL Architecture

The Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system contains three major components: a hypersonic airplane, which will transport the payload as high and as fast as possible using air-breathing propulsion; an orbiting spinning space tether, the lower tip of which will be lowered down and slowed down by one means or another, so as to meet up with the hypersonic airplane; and a grapple assembly at the tip of the space tether that will take control of the payload, and with the lift supplied by the space tether, carry the payload on into orbit. There, after the space tether has used propellantless propulsion to change its orbit and rotation, the payload will be tossed into its desired final trajectory. It would be desirable that the HASTOL system function in both directions, allowing for return of payloads from orbit to the Earth's surface. This is not a firm requirement, however, for a launch-only HASTOL system would be useful in itself, since returning from orbit is much easier than launching into orbit. The objective of our ongoing study is to optimize the combined system of airplane, tether, and grapple in order to maximize the overall system performance in terms of payload mass and delivery rate, while minimizing the life cycle cost.

Background

Let us first give some scale to the problem of launching a payload into space. In order to fly an airbreathing vehicle directly into orbit requires an airplane capable of reaching horizontal speeds of 7.8 km/s (26 kft/s or approximately Mach 25) at 150 km (490 kft) altitude or an orbital radius of 6530 km (21,400 kft). Designs exist for hypersonic airplanes capable of level flight at 3.1 km/s (10 kft/s or approximately Mach 10), and concepts exist for faster planes of Mach 12.5 and higher, but the difficulty of making and operating the hypersonic airplane rises rapidly with increasing Mach number.

There is another scale to the problem of putting things into orbit. Since space starts at about 100 km up, most people think that to get into space only involves 100 to 200 km worth of travel. What they fail to realize is that every rocket launched into orbit to date has had to travel thousands of kilometers down range to attain the necessary 7.8 km/s orbital speed. Since the distance D that must be traveled at constant acceleration a to reach a final velocity V is $D = V^2/2a$, to reach an orbital velocity of 7.8 km/s at an acceleration of one gee (a=9.8 m/s), requires covering a distance of 3100 km. Similar scaling laws apply to space tethers. If a spinning space tether is to produce a change in velocity of a third of orbital speed, or 2.6 km/s, then the tether length L for a one gee acceleration at the tether tip needs to be of order $L = V^2/a$=690 km. As will be illustrated in the following section on HASTOL Space Tether Concepts, there are many designs for space tether systems which can lower a payload grapple assembly into the upper atmosphere at grapple speeds with respect to the Earth's atmosphere ranging from 4.65 km/s (15 kft/s or Mach 15) to 3.1 km/s (10 kft/s or Mach 10) and lower, but the difficulty of operating the space tether rises rapidly with decreasing grapple speed. We are quite sure that the bridge between air and space can be crossed by using the right combination of hypersonic airplane and orbiting space tether. Finding that optimum combination is the objective of our study.

HYPERSONIC AIRPLANE

The technology for the hypersonic airplane portion of the HASTOL system is being developed by Boeing and others elsewhere and is not part of the HASTOL effort. However, vehicle performance, flight trajectory requirements, and operational aspects peculiar to tether rendezvous and payload transfer in support of development and optimization of the HASTOL system are, and form a major portion of the hypersonic airplane portion of the HASTOL team effort. The hypersonic vehicle portion of the HASTOL effort will start with an existing design[2] for the DF-9 (See Fig. 1), a multi-role, hypersonic aircraft developed by Boeing for NASA LaRC. The DF-9 can perform both cruise and space launch missions. The vehicle is designed to operate from existing runways and incorporates a low-speed propulsion system based on JP fueled, Air-core-enhanced Turbo Ramjets (AceTRs) for operations up to Mach 4.5. Above Mach 4.5 a slush-hydrogen-fueled ram/scram system powers the vehicle. While the design is optimized for long range cruise at Mach 10, the vehicle can also perform "pop-up"-type launches of satellites, and incorporates a 3 m (10-ft) diameter, 9 m (30 ft) long payload bay for that purpose. The vehicle design does incorporate a linear rocket to provide thrust at altitudes where the airbreathing systems are ineffective. One important objective of the study will be to identify HASTOL scenarios where the rocket is not needed.

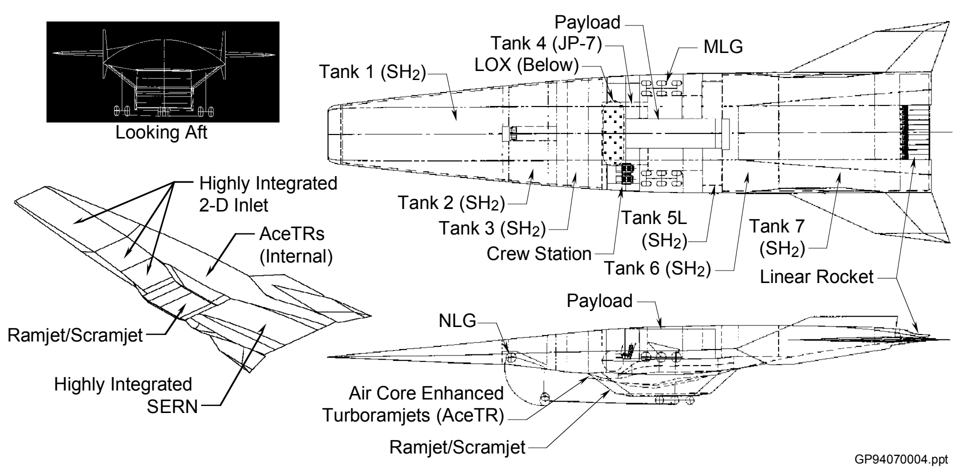

Fig. 1 - DF-9 Dual-Fuel Aerospaceplane

Our initial assessment of the application of this particular vehicle design for accomplishing the HASTOL concept indicates that at the probable 80 to 100 km rendezvous altitude, the dynamic pressure and therefore the combustor pressure will be too low for continuous cruise operation using current air-breathing hypersonic engine concepts. However, a 100 km (330 kft) rendezvous altitude was found to be readily attainable using a "pop-up" maneuver as shown in Fig. 2. This maneuver would allow the safe staging of minimally streamlined payloads, or payload/upper-stage combinations, at conditions where the velocity provided by the hypersonic aircraft could be maximized and the performance of the upper stage optimized. The current design shown in Fig. 1 is capable of carrying a 30,000 lb. (14 Mg or 14 metric ton) combination upper stage and payload to speeds of approximately 3.6 km/s (12 ft/s or Mach 12) at altitudes as high as 100 km (330 kft).

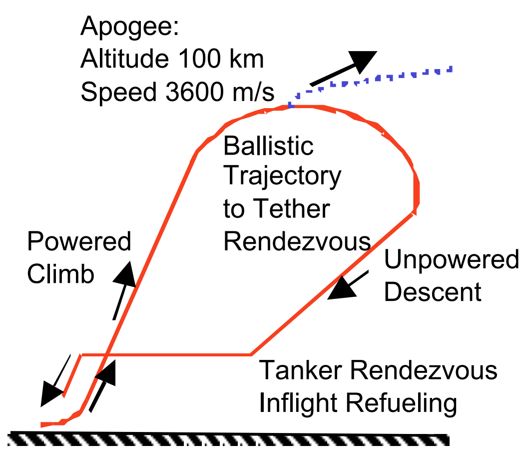

Fig. 2 - Vehicle Pop-Up To Tether Rendezvous

During the future efforts of this continuing study, the existing hypersonic airplane design will be modified, as required, to perform HASTOL type missions and the modifications incorporated into its performance simulation model. The results of the hypersonic vehicle trade study will be incorporated in the overall HASTOL system assessment. Two principal variant types will be assessed. In the first, the aircraft will rendezvous with the grapple assembly. This variant will be modified, as required, for each applicable HASTOL concept and its rendezvous geometry. In order to operate in these HASTOL modes it will be necessary to resize the existing auxiliary rocket engines and their propellant volumes for increased altitude and velocity. An enhanced reaction control system with 6-axis capability (including limited trajectory control) will also be required in lieu of the current 3-axis (attitude only) system.

A different variant that will also be studied, will have the hypersonic airplane carry the payload to an intermediate condition. From there a small rocket upper stage will carry the payload to the rendezvous with the grapple. This approach will require fewer system modifications, but will have less payload capability at a particular size due to the mass required by the rocket upper stage. Both variants will then be used to evaluate the concept through several trade studies and optimized with the tether and grapple studies.

HASTOL SPACE TETHER CONCEPTS

There are many ways of designing the orbiting spinning space tether component of the HASTOL system. The six different space tether system concepts initially studied were the: HyperSkyhook, Rotovator, CardioRotovator, CASTether/LIFTether, Tillotson Two-Tier Tether, and HARGSTOL. In our initial analyses of each concept, we assumed that the tether system would have a Tether Central Station (TCS) that was many times more massive that the tether or the payloads being handled. This was assumed so that the center-of-mass (CM) of the tether system was at the TCS. In reality, the TCS will have a finite mass, and the CM of the tether system will not be exactly at the TCS. These corrections will be taken into account in later, more detailed, tether system design studies.

Although the tether mass will usually be less than the TCS mass, we do not want to ignore the tether mass entirely. So, for each of the following concepts we have estimated the mass of the tether alone, using the data we have for the tensile strength and density of high strength materials that are presently available in commercial quantities. If the mass of the tether starts to exceed 200 times the mass of the payload, then that is an indication the particular scenario being considered is not engineeringly feasible using presently available materials, although the application might become feasible in the near future as better materials become available with higher tensile strengths at higher operational temperatures.

As we shall see later, presently available commercial materials will suffice to make the HASTOL concept work. Just a modest improvement by a factor of two over present-day materials in the ratio of the tensile strength to the density will lower the ratio of the tether mass to the payload mass to the point to where they are no longer a significant factor in the commercial feasibility of the concept. The primary message we want to leave with the Reader is: "We don't need *magic* materials like 'Buckminster-Fuller-carbon-nanotubes' to make the space tether for a HASTOL system. Present-day materials will do."

HyperSkyhook

In 1995 Zubrin proposed[3] the "Hypersonic Skyhook" as a solution to the mismatch between the attainable atmospheric speeds of a hypersonic airplane and the orbital speeds of space tethers. Since the orbital speed of the space tether decreases with increasing altitude of the tether system center-of-mass, he proposed the use of very long non-spinning tethers or "skyhooks" reaching down from very high altitudes. His analysis showed that because a hanging tether must be tapered to support its lower end in the gravitational field of the Earth, achieving a HyperSkyhook tether tip rendezvous with a 5.0 km/s (16 kft/s or Mach 16) airplane would require a HyperSkyhook tether mass of 25 times the payload mass. Trying to lower the tether tip speed to 4.0 km/s (13 kft/s or Mach 13) would require a HyperSkyhook tether mass greater than 200 times the payload mass. Unless a major breakthrough occurs in high strength tether materials, such as the commercial development of carbon nanotube fibers, it does not seem possible to push the non-spinning tether HyperSkyhook concept down to speeds of 3.1 km/s (10 kft/s or Mach 10).

Rotovator™

The standard method of attaining a low tether tip velocity is to use a rapidly spinning tether, or Rotovator™. The Rotovator concept was invented in 1967 by Artsutanov and reinvented by Moravec in 1977, who did the first thorough analysis[4] of it. Since the Rotovator must reach down from orbital altitudes into the upper atmosphere to match speeds with the hypersonic airplane, the length of the tether and the orbital altitude are necessarily interrelated, with the orbital altitude of the tether center-of-mass (CM) being the length of the tether plus a nominal 100 km for the thickness of the atmosphere. The longer the tether, the higher the orbital altitude and the slower the velocity of the tether system CM.

Rotovator™ Tether Mass: The mass of a rapidly spinning tether in free space is determined primarily by the tip speed of the tether, not the tether length or the tether tip acceleration. The basic equation for the ratio of the mass M_T of one arm of a spinning tether to the mass M_P of the payload plus grapple on the end of the tether arm, was derived by Moravec in 1978 in an unpublished paper, based on a previously published paper[4], and is:

$$\frac{M_T}{M_P} = \sqrt{\pi}\left(\frac{V_T}{V_C}\right)\exp\left[\left(\frac{V_T}{V_C}\right)^2\right]\mathrm{erf}\left(\frac{V_T}{V_C}\right) \qquad (1)$$

Where the error function

$$\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}}\left[z - \frac{z^3}{1!\times 3} + \frac{z^5}{2!\times 5} - \ldots\right] \qquad (2)$$

varies from erf(0)=0 to erf(>3)=1.0, while erf(1)=0.843, V_T is the tether tip speed, and $V_C=(2U/Fd)^{1/2}$ is the maximum tip speed of an untapered tether, where U is the ultimate tensile strength of the tether material, d is its density, and $F>1$ is an engineering safety factor derating the "ultimate" tensile strength to a safer "practical" tensile strength. Equation (1) shows specifically that the mass ratio of a spinning tether is a function of the ratio of the tether tip speed to the characteristic velocity (V_T/V_C) only, and to first order does not depend on the tether tip acceleration or the length of the tether. The exponential growth in the mass ratio with the *square* of the velocity ratio seen in Eq. (1) means that attempting to achieve tip velocities significantly higher than the characteristic velocity of the material rapidly leads to unfeasible mass ratios. Equation (1), however, is for spinning tethers in deep space, and does not include gravity gradient forces, which can be significant for long tethers that are operating close to the Earth.

The mass ratio of a long tether near the Earth will depend not only on the tip velocity of the tether, but also the length of the tether and the gravitational acceleration on the tip of the tether.[5-7] This will be true for most of the tether systems being considered for the HASTOL architecture. There is no simple analytical equation that takes these gravity gradient forces into account, and the mass ratio needs to be numerically integrated for each case. Thus, we have used a numerical integration program to generate a table of tether mass ratios for Rotovator tethers of various lengths L, spinning at various tip speeds V_T, with the center of mass of the tether at the orbital radius $R_O=R_E+h+L$, and moving at a circular orbit velocity of $V_O=(GM_E/R_O)^{1/2}$, where h=100 km is the nominal payload pickup altitude, R_E=6378 km is the radius and $M_E=5.98\times10^{24}$ kg is the mass of the Earth, and the gravitational constant $G=6.67\times10^{-11}$ m^3/kg-s^2. The lower end of the orbiting, spinning tether then reaches down into the atmosphere to match speeds with a hypersonic airplane moving at a hypersonic velocity $V_H=V_O-V_T-470$ m/s, where 470 m/s is the velocity through inertial space of the atmosphere at 100 km altitude at the equator of the rotating Earth.

We found that spinning tethers that were very short had a lower orbital altitude and therefore higher orbital velocity, so they needed a higher tip velocity to match speeds with a hypersonic airplane moving at a given hypersonic velocity. Thus, their mass ratio increased exponentially as the square of the velocity because of Eq. (1). We also found that tethers that were very long were orbiting more slowly, and thus needed less tip velocity, but because the gravity gradient forces on the tether increased with tether length, the mass ratio increased because of the increased gravity force. After a lengthy search through the parameter space, we found that there was a broad minimum in the mass ratio that occurred when the tether length and the tether tip velocity were such that the centrifugal acceleration at the tether tip was approximately 16 m/s^2 (52 ft/s^2 or 1.6 gees).

Idealized Rotovator™ Results: The results of our first cut analysis are summarized in Table 1. It should be emphasized that in generating Table 1 we have made two highly idealistic assumptions. First, we assumed that the Tether Central Station is much more massive than the tether. If this is not true, then the tether mass ratios given in Table 1 could rise by up to a factor of 2. The factor of 2 would be the case where there is no TCS at all, and the counterbalance to the tether arm is an equally massive arm stretching out in the opposite direction from the CM. Second, we assumed that we are dropping off a payload at the same time (or nearly the same time) as we are picking up a payload. This assumption produces the ideal result that the load on the tether does not change, the CM of the tether does not change, and the orbit of the CM of the total tether facility around the Earth does not change.

In prior studies of systems for picking up payloads from low Earth orbits and tossing them to the Moon[6] and Mars[7], we showed that practical spinning tether systems could be designed without using any of the above ideal assumptions, that were capable of carrying out those difficult payload pickup and toss tasks while massing less than 30 times the payloads being thrown. As we move further into our HASTOL studies, we will go through the same procedure of replacing these idealistic first cut tether system designs with progressively more realistic designs.

For the calculation of the tether to payload mass ratio, we used data available for Spectra™ 2000, a polymer made by AlliedSignal with an ultimate tensile strength of 4.0 GPa (580,000 psi), a specific density of 0.97, and a derated (safety factor of F=2) characteristic velocity of 2030 m/s (6660 ft/s). This material, along with others, is discussed in more detail later in the paper.

In Table 1, the column labeled '2x' is for a future material (Spectra™ X000?) that has twice the tensile strength to density ratio of presently available Spectra™ 2000, while the column '10x' is a "placecard" for some far future material (derated carbon nanotubes?) that has ten times the ratio of tensile strength to density of the presently available Spectra™ 2000 fiber.

From looking at Table 1, we can see that the use of present-day Spectra™ in a HASTOL system will enable the Rotovator system to work down to about 3.4 km/s (Mach 11) without the tether becoming too heavy. Column '2x' indicates that it only takes a small improvement in tether materials for the Rotovator concept to work down to 3100 m/s (Mach 10). Column '10x' indicates that carbon nanotubes would be "overkill" as far as the Rotovator concept is concerned. We don't need carbon nanotubes to make a HASTOL system, as we will need to retain some amount of mass in the tether in order to keep the tether system itself from being pulled out of orbit by the payload!

Table 1 - Minimum Mass Ratio Rotovator™ Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra™	2x	10x
400	6878	7614	2494	4650	15.0	10.4	2.4	0.37
500	6978	7559	2749	4340	14.0	16.7	4.2	0.56
600	7078	7506	3006	4030	13.0	27.1	5.9	0.65
700	7178	7453	3263	3720	12.0	44.0	8.2	0.73
800	7278	7402	3522	3410	11.0	71.8	11.6	0.90
900	7378	7352	3782	3100	10.0	117.6	16.3	1.07

Realistic Rotovator™ Results: We recently have generated some new results where we assumed a more realistic design for the Rotovator™ Facility and a more realistic operational scenario. In this analysis, we assumed a payload mass of 15 Mg (33,000 lb), grapple assembly mass of 0.5 Mg, tether length of 600 km, pickup altitude of 100 km (330 kft), and pickup velocity of 4.1 km/s (13 kft/s), which requires the hypersonic aircraft to fly at 3.6 km/s (12 kft/s or Mach 12) at the equator so that it can take advantage of the 470 m/s (1500 ft/s) rotation of the Earth. This more realistic operational scenario assumed that there would be *only* a pickup of the payload, without a compensating drop-off of a payload. This, in turn, required that the CM of the

Rotovator Facility be in an initially elliptical orbit with an eccentricity of 0.0062, so that after pickup of the payload, the Rotovator Facility dropped into an orbit with a perigee such that the tip of the spinning tether did not hit the atmosphere.

The analysis is still in the process of being optimized, but with the assumption that we use Spectra™ 2000 material with a safety factor of 2, then the required mass of the tether alone was calculated to be approximately 91 times the payload mass (about double that in Table 1), while the mass of the Tether Central Facility needed to be 110 times the payload mass, for an overall Rotovator Facility mass ratio of 201. If a stronger material becomes available, that has twice the strength-to-density of Spectra™ 2000, then an optimized Rotovator Facility with a tether length of 600 km would operate in a slightly more elliptical orbit with an eccentricity of 0.0145. The mass of the tether alone would now be only 11 times the payload mass, while to avoid the payload from dragging the Rotovator Facility down into the atmosphere, the TCS mass would actually have to increase to 120 times the payload mass! The total Rotovator Facility mass would then be 131 times the payload mass. We expect that these total mass ratios will drop as we optimize the system.

Although these mass ratios are high, they are not impractical, considering that the Rotovator Facility can be used to "build itself" by starting out small, then picking up tether and power modules to build up the length, thickness, and taper of the tether, and picking up solar power modules to build up the power supply needed by the propellantless electrodynamic tether propulsion system[6] that maintains the Rotovator Facility orbital altitude and spin speed. Carroll has shown[5] that tether facilities are capable of pickup up a payload with the end of a tether, then "tossing" the payload into an orbit where the payload later can rendezvous and dock with the CM of the facility (somewhat like tossing a peanut into your mouth)!

The important point to make about our study results so far, is that an orbiting spinning space tether built using existing space tether materials, and using the simplest existing tether facility design, can be used to pick up a payload from an existing design for a hypersonic airplane that is capable of taking a payload to an altitude of 100 km (330 kft) altitude while moving at 3.6 km/s (12 kft/s or Mach 12). Thus, the HASTOL system combination of a Spectra™ 2000 Rotovator™ and a DF-9 Aeropaceplane is capable of taking payloads from the surface of the Earth and putting them into space. The other HASTOL concepts we will discuss later may prove to be better, but this concept will suffice.

<u>CardioRotovator</u>

The CardioRotovator concept consists of a Tether Central Station in an elliptical orbit, with a single long tapered tether. The tether rotation rate is chosen to be exactly twice the orbital period. The phase of the rotation is chosen such that when the Tether Central Station is at perigee, or closest to the Earth, the tether is pointing straight up, as is shown in Fig. 3. Then, when Tether Central Station is at apogee, or furthest from the Earth, the tether is pointing straight down at the Earth, reaching deep into the atmosphere for the payload pickup.

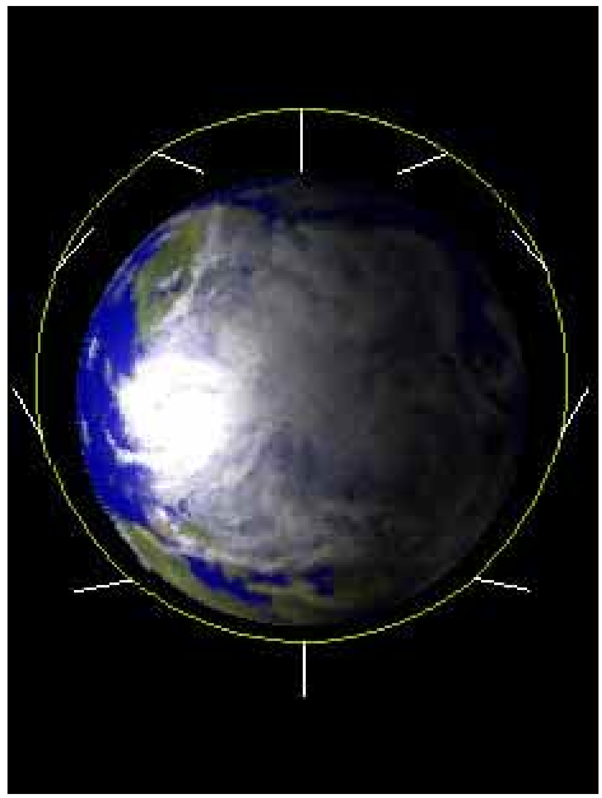

Fig. 3 - CardioRotovator Concept

As can be seen in Fig. 3, at intermediate points, the tether is pointing away from the Earth and does not penetrate below the Tether Central Station altitude except near the touchdown point below the apogee point. The trajectory of the tip of the tether is approximately heart-shaped, which lead to the name of "CardioRotovator" for the system concept. Unlike the circular orbit Rotovator system, the tether length and tip velocity of a CardioRotovator cannot be chosen independently. Once a particular apogee radius R_A is chosen, that determines the length of the tether, since $L=R_A-R_E+h$. Then, once a particular perigee radius R_P is chosen, that, along with the apogee radius, fixes the orbital period P to be:

$$P = \pi \left\{ \frac{(R_A + R_P)^3}{2GM_E} \right\}^{1/2} \quad (3)$$

The rotational period p of the spinning tether itself is then also determined, since the design of the CardioRotovator requires that $p=P/2$. This rotational period, together with the tether length L, then determines the tether tip speed as $V_T=2\pi L/p=\pi L/P$.

In Table 2, we have tabulated some relevant examples of the CardioRotovator system parameters, assuming that in all cases the perigee altitude of the Tether Central Station is 500 km, which is just outside the International Space Station nominal altitude of 400 km. With these assumptions, the CardioRotovator tether tip acceleration levels were found to between 0.43 and 0.66 gees, acceleration levels easily accommodated by human passengers. Again, for Table 2, we have assumed an idealistic situation where the TCS has an infinite mass and that a payload pickup is compensated by a payload drop-off.

By comparing Table 1 for the Rotovator systems with Table 2 for the CardioRotovator systems, it is seen that the CardioRotovator gives somewhat better results than the Rotovator. In general, however, the length of the CardioRotovator tether is much longer than the length of the Rotovator tether, which leads to greater concern about collisions of the tether with other objects in space. This concern is partially compensated by the fact that the CardioRotovator tether spends most of its time at high altitudes where there is less traffic.

Table 2 - CardioRotovator Tether Parameters for HASTOL Application

Tether Length	Orbital Radius	Orbital Velocity	Tip Velocity	Tip Accel.	Hypersonic Airplane Velocity		Tether to Payload Mass Ratio		
L	R_O	V_O	V_T	a	$V_H= V_O-V_T$-470 m/s		M_T/M_P		
(km)	(km)	(m/s)	(m/s)	(m/s^2)	(m/s)	Mach	Spectra	2x	10x
1000	7478	7147	2076	0.43	4601	14.8	10.8	3.1	0.39
1200	7678	7004	2440	0.50	4094	13.2	22.2	5.2	0.55
1400	7878	6868	2789	0.56	3608	11.6	44.7	8.4	0.75
1600	8078	6737	3124	0.61	3143	10.1	87.8	13.4	0.97
1800	8278	6611	3445	0.66	2695	8.7	168.5	21.0	1.24

Two-Stage Rotovator

The Tillotson Two-Tier Tether (TTTT or T4)[8] consists of a long, large, tapered "first stage" spinning tether, at the end of which is a smaller "second stage" spinning tether as shown in Fig. 4. The T4 is essentially a two-stage Rotovator. The use of two tiers or two "stages" in the design of a spinning tether decreases the overall ratio of the tether launch system mass to payload mass, in a manner similar to the benefits of the lower mass ratio obtained when using a two-stage rocket in a rocket launch system.

Since the ratio of the tether mass to the payload mass of a spinning tether increases as the exponential of the square of the tip velocity (see Eq. 1), large reductions in overall mass ratio can be obtained by dividing up the total tip velocity required into nearly equal amounts. In a typical HASTOL scenario where a tether tip velocity of 3.6 km/s (12 kft/s) is needed to meet, say, a Mach 11 hypersonic aircraft moving at 3.4 km/s (11 kft/s), the tether mass required might be 80 times the payload mass. If instead, the first stage tether rotates at a tip speed of 1.8 km/s (6 kft/s), while the second stage tether also rotates at a tip speed of 1.8 km/s, the combined velocities reach the 3.6 km/s needed for the pickup, but the combined mass of the two tethers could be as little as 21 times the mass of the payload.

In the T4 concept, there will be a Tether Central Station (TCS) (assumed to have infinite mass for this first cut analysis), around which will be spinning a one-arm first stage tether, with an effective radius of rotation around the TCS of R_1. At the end of the first stage tether will be a stiff pivot bearing supported at both ends by the split end of the first stage tether, as shown in Fig. 4. This pivot bearing will be the central support point for the spinning second-stage tether, which will have a radius of rotation R_2. The total length, when both tethers are aligned along the nadir, will be $L=R_1+R_2$. Since we want the pickup to take place at an altitude h=100 km (330 kft), this determines the orbital radius of the TCS to be $R_O=R_E+h+L$, where R_E is the radius of the Earth. The orbital velocity is then just $V_O=(GM_E/R_O)^{1/2}$, where G is the Newtonian gravitational constant and M_E is the mass of the Earth.

ratio for a single stage single arm tether as shown in equation 1.

$$M_{2STAGE} = 2\left[M_1\left(\frac{V_T}{2V_C}\right)\right]^2 + 3M_1\left(\frac{V_T}{2V_C}\right) \qquad (4)$$

Equation 5 describes the total tether mass in more fundamental terms:

$$\frac{M_T}{M_P} = 2\pi\left(\frac{V_T}{2V_c}\right)^2 \exp\left[2\left(\frac{V_T}{2V_C}\right)^2\right]\left[\operatorname{erf}\left(\frac{V_T}{2V_c}\right)\right]^2 + 3\sqrt{\pi}\left(\frac{V_T}{2V_C}\right)\exp\left[\left(\frac{V_T}{2V_C}\right)^2\right]\operatorname{erf}\left(\frac{V_T}{2V_C}\right) \qquad (5)$$

In Table 3, we have tabulated some relevant examples of the T4 system parameters, assuming that in all cases the total tip speed is evenly divided between the two stages. Because the second stage tether has a shorter radius than a single-stage tether for equivalent total tip speed, the acceleration at the tip is higher than for a single stage system. For this analysis we assumed the ratio of stage 1 tether radius to stage 2 radius is 5:1. With that assumption, the cases described in Table 3 have a maximum acceleration of 2.9 gravities, which is less than the 3-g maximum acceleration experienced during a Space Shuttle launch. It is possible to change the ratio of stage lengths and tip velocities to adjust system mass, acceleration, and dynamics.

The T4 approach to the design of the Rotovator for a HASTOL system is much more complicated in design and dynamics than a simple one stage Rotovator. The plan is to baseline the one-stage Rotovator for the study, but to carry out analyses of the T4 system in parallel. If the mass of the one-stage tether grows to where its mass begins to cast doubt on the engineering or financial feasibility of the HASTOL concept, then we always have the T4 two-stage concept available in order to drastically cut the tether mass needed.

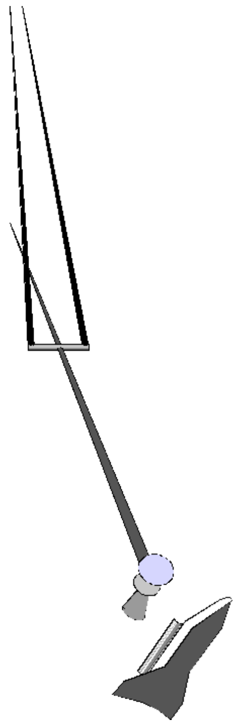

Fig. 4 - Tillotson Two-Tier Tether (T4) Concept

Dividing the total tip velocity V_T evenly between the two stages gives each stage a tip velocity of $V_T/2$. To distribute the mass of the second stage tether evenly about its center of rotation, the second stage tether must have two arms with equal mass on each side of the pivot bearing. The second stage tether mass is therefore twice as great as a single-arm tether with tip velocity $V_T/2$. The first stage tether is a single-arm tether which must support the mass of the payload plus the second stage tether. The total tether system mass is the sum of the first and second stage masses. The relative advantage of a T4 system compared to a single stage rotovator is expressed by Equation 4, where $M_1(V_T/V_C)$ is the mass

Table 3 - Tillotson Two-Tier Tether Parameters for HASTOL Application

1st Tier Tether Radius	2nd Tier Tether Radius	Total Tether Length	TCS Orbital Radius	TCS Orbital Velocity	Total Tip Velocity Needed	Hypersonic Airplane Velocity		Total Tether to Payload Mass Ratio	
R_1	R_2	L	R_O	V_O	V_T	$V_H = V_O - V_T - 470$ m/s		M_T/M_P	
(km)	(km)	(km)	(km)	(m/s)	(m/s)	(m/s)	Mach	Spectra	2x
333	67	400	6878	7614	2494	4650	15.0	4.83	1.65
417	83	500	6978	7559	2749	4340	14.0	6.91	2.18
500	100	600	7078	7506	3006	4030	13.0	9.91	2.85
583	117	700	7178	7453	3263	3720	12.0	14.2	3.71
667	133	800	7278	7402	3522	3410	11.0	20.6	4.81
750	150	900	7378	7352	3782	3100	10.0	29.9	6.23

CASTether/LIFTether

Another concept for the space tether portion of the HASTOL system uses two separate methods for operating the tether. The Cast Ahead Supersonic Tether or CASTether concept involves "casting" the tether ahead of the Tether Central Station and using aerodynamic drag to slow the tip of the tether down to hypersonic speeds. The Lift Into Freefall Tether concept involves arranging for the aerodynamically slowed tether to be vertical just as the TCS is passing overhead. The TCS will then initially "lift" the payload vertically upwards, then pull it along behind into orbit. The two concepts are illustrated in our previous publication.[1] We have yet to carry out an analysis of this concept, so we will not discuss it further here.

HARGSTOL

The final method of accomplishing the HASTOL concept is to compromise, and allow the partial use of a rocket upper stage or a rocket-powered grapple to complete the payload transfer between the hypersonic airplane and the grapple assembly at the end of the space tether. Thus, instead of the HASTOL system, we will have the HA**R G**STOL or Hypersonic Airplane, Rocket Grapple, Space Tether Orbit Launch system. This concept has a number of possible variations. The normal method would be to have the rocket augmented grapple on the tip of the tether. The tether system would slow the tip down as much as possible using one of the tether tip slowing techniques, and the airplane would fly as fast and high as possible, and the rocket system on the grapple would make up any speed difference. The grapple would need to be refueled periodically. This could be done at each payload pickup, or there could be periodic pickups of propellant tanks, with the empty tanks added to the Tether Central Station ballast.

A variation on this concept would be to have the major part of the tether mass be a permanent part of the space tether system, but the "tip" of the tether and the rocket grapple would be carried by the hypersonic airplane. At some time interval before the rendezvous time, the grapple would be separated from the airplane, pulling out the tether, which would be made of material capable of coping with the hypersonic heating and stress. The rocket grapple would then climb in altitude and speed to meet up with the lower end of the space tether out in space away from the atmosphere, while the airplane stays in the atmosphere at an optimum cruise altitude. The grapple grabs the end of the tether, the payload is pulled free from the airplane, and lifted into space by the tether.

The ultimate rocket grapple concept would have the rocket take the grapple from the hypersonic airplane all the way to the Tether Central Station, pulling out tether from the payload. Since for normal ΔV requirements the tether mass would be much larger than the payload mass, it is obvious that a better technique would be to meet the downgoing tether from the Tether Central Station "halfway". Finding the optimum ratio for the length of the airplane tether versus the space tether would be part of the overall system optimization. This concept, with the rocket grapple coming from the airplane without carrying the payload, would only be usable for taking payloads into orbit. For two-way systems, it would be necessary to have the rocket grapple on the end of the space tether, and have the rockets on the grapple capable of accelerating both the grapple and the payload.

The most important feature of all the possible HARGSTOL systems is that we KNOW we can make them work, no matter how poor the ultimate performance of the hypersonic airplane and the space tether. All it requires is that the rocket grapple be loaded with enough propellant to close the velocity gap. Since the mass ratio of the propellant to grapple-plus-payload is exponential in the grapple ΔV, and the rocket ΔV is low because of the ΔV contributions of both the airplane and tether, the propellant required should be low.

SPACE TETHER ISSUES[6,9]

The space tether portion of the HASTOL system has a number of issues that must be dealt with other than the method of operation, including surviving damage by meteorites and space debris, operating at hypersonic speeds in the upper atmosphere, avoiding collisions with other spacecraft, and safe and reliable operation at low system mass.

Tether Survivability

For a tether transport system to be economically advantageous, it must be capable of handling frequent traffic for many years despite degradation due to impacts by meteorites and space debris. Yet, the tether mass must be minimized to reduce the cost of fabricating and launching the tethers. These two requirements present conflicting demands upon the tether design that make conventional single-line tethers impractical for the HASTOL application. For a single-line tether to achieve a high probability of survival for many years, it must be very thick and massive. Fortunately, a low mass survivable tether design exists, called the Hoytether™, which can balance the requirements of low weight and long life[9]. As shown in Fig. 5, the Hoytether is an open net structure where the primary load bearing lines are interlinked by redundant secondary lines. The secondary lines are designed to be initially slack, so that the structure will not collapse under load. If a primary line breaks, however, the secondary lines become engaged and take up the load. Note in Fig. 5, that four secondary line segments replace each cut primary line segment, so that their cross-sectional area need only be 0.25 of the primary line area to carry the same load. Typically, however, the secondary lines are chosen to have a cross-sectional area of 0.4 to 0.5 of the primary line area, so as to better cope with multiple primary and secondary line cuts in the same region of the tether. This redundant linkage enables the Hoytether™ structure to redistribute loads around primary segments that fail due to meteorite strikes or material failure. Consequently, the Hoytether structure can be loaded at high stress levels, yet achieve a high margin of safety.

Tether System Collision Avoidance

There are many objects in space, ranging from micrometeorites to operational spacecraft with 10–meter–long solar array panels. We can design interconnected multiple strand open net Hoytether™ structures that can reliably (>99.9%) survive in space for decades despite impacts by objects up to 30 cm (1 ft) or so in size. Objects larger than one meter will impact all the strands at one time, cutting the tether. These large objects could include operational spacecraft, and they will also be damaged by the impact. Objects larger than 30 cm are all known and tracked by the U.S. Space Command. There are about 6000 such objects in low and medium Earth orbit, of which an estimated 600 will be operational spacecraft in the 2005 time frame. For an atmospheric tether application, we have estimated that, if no traffic control measures are instituted, a 20 km long tether in an orbit grazing the upper atmosphere has a 4% chance of being cut by one of the 6000 large objects during a one year mission, and an 0.4% chance of striking one of the 600 operational spacecraft. Longer tethers will have proportionately larger probabilities. It will therefore be incumbent on the HASTOL system operators to maintain contact with the U.S. Space Command and keep an accurate inventory of the known large objects. They then need to control the tether system CM orbital altitude and phase, the tether rotation rate and phase, and the tether libration and vibration amplitudes and phases, to insure that the tether system components do not penetrate a volume of "protected space" around these large orbiting objects.

Tether Safety Factor and System Reliability

When a tension member such as a tether is developed, it is normally designed to operate at a load level somewhat lower than the maximum it could support without breaking. This derating provides margin of error in case of imperfections in the material or the construction. Typically, a single line tether is designed to carry a maximum load that is 50% of its breaking limit. This tether would thus have a "design safety factor" of F=1/0.50=2.0. For the Hoytether[9], we define the safety factor as the ratio of the maximum load capacity *of both primary and secondary lines* to the design stress load S_P of the *primary lines alone*.

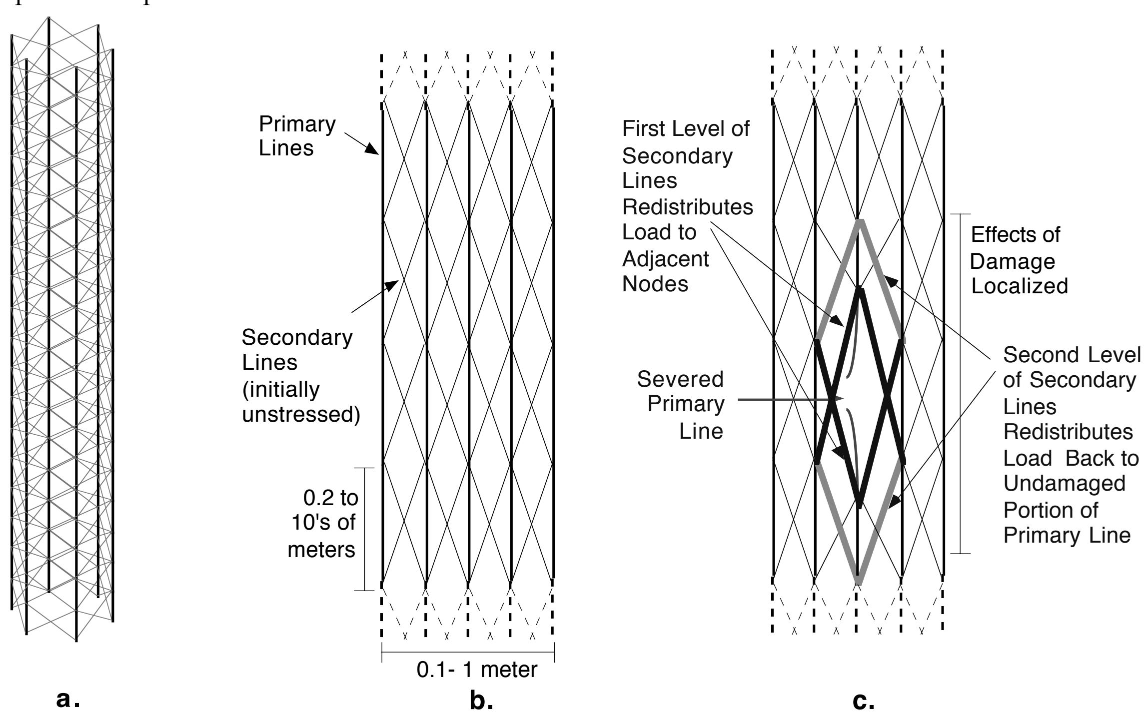

Fig. 5 - The Hoytether™ design and its response to a cut line

$$F=[1+(N_S A_S)/(N_P A_P)]/S_P \quad (6)$$

where N_P and N_S are the number of primary lines and secondary lines, and A_P and A_S are their respective cross-sectional areas. For a typical tubular Hoytether™ there are twice as many secondary lines as primary lines so $N_S=2N_P$ and Eq. (6) reduces to $F=[1+2A_S/A_P]/S_P$. For the case where the secondary line area is half the primary line area or As=0.5Ap and the stress on the primary lines is 67% of the ultimate tensile strength of the material or $S_P=0.67$, then the Hoytether™ safety factor would be: F=[1+2(0.5)]/0.67=3. This definition of the Hoytether™ safety factor provides the same measure of the strength-to-weight ratio of the Hoytether structure as it does for a single-line tether. However, this definition of the safety factor does not accurately represent the margin of safety for the Hoytether. Because the Hoytether has redundant links that can reroute stress around parts of the tether that have failed, it is possible to load the Hoytether at a large fraction of the capacity of the primary lines (i.e.- small "line safety factor") and still have a large margin of safety against parting.

To study the optimization of the Hoytether structure for high-load applications, we performed a series of simulations of variations of the structure using our "SpaceNet" tether simulation program[6]. The SpaceNet program uses a combination of finite-element methods with a structural relaxation scheme to calculate the effects of damage to complex 3-D net structures such as the Hoytether. The results of our analyses indicate that the design of an optimal Hoytether depends upon how much of its mission duration will be spent under high load. Consequently, there are two classes of Hoytether™ designs, one for tethers that are always under high load, and one for tethers that are heavily loaded for brief periods only.

Continuous High Load Tether: If the tether will be under high load for most of its mission, then it should be designed with secondary lines slack at the expected load level. This will enable the tether lines to remain spread apart at all times, minimizing the chances of a single impactor cutting several lines. For this case, SpaceNet simulations showed that a near-optimal tether design would be a cylindrical Hoytether with a large number of primary lines (~20) stressed at 75% of their maximum load and with initially-slack secondary lines that each have a cross-sectional area 0.4 times that of a primary line. Simulations showed that splitting the tether up into a large number of primary lines prevented the stress energy released by a cut of one of the primary lines from overloading neighboring primary lines before the secondary lines could become taut enough to take up the released stress and pass it around the cut primary line segment to the uncut primary line segments above and below the cut segment.. From Eq. (6), such a tether will have a design safety factor of 2.4. However, the redundant nature of the structure will make the Hoytether far more reliable than a single line tether with the same safety factor. Simulations with the SpaceNet program have shown that this tether design can withstand multiple cuts on a single level. In fact, even if all of the primary lines on one level are cut (one at a time), the secondary lines will support the load.

Intermittent High Load Tether: The HASTOL Space Tether facility, however, would likely be loaded at high levels for only a few hours at a time. Therefore, it is possible to reduce the tether weight by designing it to have slack secondary lines at the load level experienced during its long "off-duty" periods, but to have the secondary lines bear a significant portion of the load during a brief high-stress operation such as a payload catch-and-throw operation. During the high-stress period, the loading of the secondary lines will cause the structure to collapse to a cylindrical tube. Once a payload is released and the stress is reduced, however, the tether lines will spread back apart. If this high-load period is brief, it will only slightly increase the chances of tether failure due to impact by a large object. Simulations indicate that a 20-primary line Hoytether with the secondary line areas 1/4 of the primary lines can be safely loaded to 85% of the primary line capacity during peak stress operations. The design safety factor of this tether from Eq. (6) is F=1.75. In this paper we will use a more conservative safety factor of F=2.

Space Tether Materials

The space tether used in the HASTOL system will consist of a long strength member made of a high strength, low density polymer, with a "hypersonic" tip made of a high strength at high temperature, atomic-oxygen resistant material. Woven into the initial 10 km of the polymer tether nearest the Tether Central Station will be an aluminum wire conductor to be used by the Hoyt Electrodynamic Force Tether (HEFT) propulsion system[6] built into the tether and used by the TCS to control the tether system orbit and spin parameters.

High Strength Main Member: The two candidate polymers for the high tensile strength main portion of the tether, Spectra™ and Zylon™, are both stronger per pound than either steel or Kevlar™ polymer fiber. Their "characteristic velocity", defined as the maximum tip speed of an untapered tether, is: $V_C=(2U/d)^{1/2}$, where U is the ultimate tensile strength of the material and d is its density. Spectra™ 2000 has a U=4.0 GPa, d=970 kg/m^3 and V_C=2872 m/s, while Zylon™ has a U=5.8 GPa, d=1560 kg/m^3 and V_C=2727 m/s. Both of these materials are commercially available in tonnage quantities with reasonable prices and delivery times. These polymer materials are sensitive to attack by atomic oxygen (AO), however, so the portions that get near the atmosphere would probably be coated with a proprietary AO-resistant resin coating available from Aeroplas.

Hypersonic Tip: The material for the hypersonic tip will not only have to withstand attack by atomic oxygen, but maintain a moderately high strength at high temperatures. We have estimated that the tether temperature due to air drag heating will range from room temperature (300K or 27C) for a tether speed through the air of 3 km/s at 120 km altitude, up to as high as 2100K (1830C) for a relative speed of 5 km/s at 80 km altitude. The candidate materials and their ultimate tensile strength in GPa (gigapascals) as a function of temperature are summarized in the Table 4. (For reference, 1 GPa = 10^9 N/m^2 = 145,000 psi). To allow a relative comparison of the suitability of the various different tether materials for use in various spinning tether systems, we also included in Table 4 the density *d* and the room temperature "characteristic velocity" $V_C=(2U/d)^{1/2}$ of the material, which is the maximum attainable tip speed of an untapered spinning tether made solely of that material. For reference, the melting points of some of the materials in Table 3 are: Al–660C, Ti–1660C, Ni–1453C, W–3410C, Al_2O_3–2015C, SiC–2700C, and SiO_2–1610C.

Table 4 - Tether Material Tensile Strength (GPa) vs. Temperature

Material	V_C (km/s)	Density d (g/cc)	20 C	300 C	600 C	800 C	1000 C	1200 C
Spectra 2000	2.87	0.97	4.0	-	-	-	-	-
Zylon (PBO)	2.73	1.56	5.8	3.7	-	-	-	-
Quartz Glass (SiO_2)	1.81	2.20	3.6	3.6	3.6	3.6	3.6	?
S-glass	1.94	2.50	4.7	?	?	?	?	?
Carbon	2.77	1.80	6.9	?	?	?	?	?
Carbon/Ni-coated	2.12	2.68	6.0	?	?	?	?	?
Tyranno (SiTiCO)	1.66	2.55	3.5	3.5	3.5	3.5	3.5	3.5
Textron β-SiC	2.19	2.93	7.0	6.6	6.0	5.6	5.2	4.5
0.72 β-SiC/Ti-coated	1.72	3.37	5.0	4.8	4.3	4.0	3.7	3.2
Altex (Al_2O_3/SiO_2)	1.21	3.30	2.4	2.4	2.4	2.4	2.4	1.5
Nextel (α-Al_2O_3)	1.30	3.88	3.3	?	?	?	?	?
0.65 Nextel/Al-coated	0.97	3.40	1.6	1.4	?	?	?	?
Tungsten Wire	0.55	19.35	2.9	2.9	2.9	2.9	2.9	2.9

GRAPPLE AND PAYLOAD TRANSFER ISSUES[8]

In order for successful rendezvous, docking, and transfer of the payload to occur, some basic functions must be performed by one or more of the HASTOL system architecture elements, which include the grapple assembly. The following basic functions have been identified and the grapple assembly design process must consider all of them:

- Establishing a known absolute location for rendezvous, capture, and transfer and keeping it updated
- Establishing and updating relative position between the payload and the grapple assembly
- Recognizing the defined rendezvous point
- Closing the gap to the rendezvous point
- Payload/grapple docking
- Payload separation from the hypersonic vehicle
- Retention of payload on grapple during transfer

Several grapple design requirements, drivers, and concerns have resulted from or are associated with the identification of these functions. Rendezvous, docking, and payload transfer will occur at around 100 km (330 kft) altitude in the presently planned HASTOL scenario. The atmosphere is not very dense at that altitude. There will be significant heating, but not much dynamic pressure despite the high velocities involved. The grapple assembly will therefore not need to be streamlined to any great extent, although it will have to withstand significant heating for its short duration in the atmosphere. The amount of heating will depend upon the exact rendezvous altitude and speed, and the "height" of the upper atmosphere at the time of the rendezvous. Later analysis will also show a clearer picture of the effects of thermal cycling due to multiple atmospheric passages. It will also aid in future material specifications.

The tethered grapple assembly motion at the point of capture must be in-plane with the payload. Control of either the grapple assembly or the payload (payload itself or the hypersonic vehicle) must be possible to insure a successful docking. Structural loading of the grapple assembly must be taken into account for rendezvous as well as for capture impact and transfer of the 14 Mg (14 metric tons or 30,000 lb) payload. No damage should occur to the payload.

A conservative assumption is that there will only be one capture attempt possible per mission. As a result, maximizing the capture opportunity window is a grapple design objective. This assumption has also resulted in a requirement for the capture to be as automated as possible; a Go/No Go decision initiated prior to the actual capture by ground control or pilot, should there be one, will be included in the grapple assembly design. It is assumed that abort modes will be defined prior to each HASTOL mission for the specific client, though efforts are on-going to identify abort modes that can be built into the system, for instance, establishing the bounds of an "attempt-to-transfer window," and a "payload out-of-bounds" window.

Other grapple design issues deal with the "no damage" to client payload policy and communications issues. The payload's safety during transfer must be insured, which means either the payload must not tumble during transfer, or it must be protected so limited tumbling can be accounted for at no consequence. The potential of communication loss at each phase of the payload transfer scenario must also be considered.

A preliminary conceptual CAD drawing of one possible grapple assembly option for the tether is shown in Fig. 6. It features a circular "attach ring" at the bottom, which will mate with grapple hooks on the payload. The attach ring is connected to the rest of the end mass via a six-degree-of-freedom, multiple-shock-absorber-strut suspension cradle. In the suspension cradle, all of the members are designed to compress as necessary, should the payload and grapple mechanism contact at some non-zero speed or some slightly non-tangential angle. The struts in the suspension cradle will also provide shock-absorber type damping of the resulting movement of the attach ring relative to the heavier end mass cylindrical structure at the top, which contains a tether winch, batteries, the reaction control system and its propellant, and the command, control and guidance electronics.

The ring and the suspension leg elements would be made of materials selected to withstand heating from the hypersonic molecular flow at the rendezvous altitude. This eliminates any need for an aerodynamic cone or shroud, which would increase the aerodynamic drag on the assembly compared to the mostly empty strut structure presented to the hydrodynamic molecular flow. The "ends up" cylinder of the upper portion of the grapple assembly is already aerodynamically stable. Adding a forward-facing conical aerodynamic "shield" to it would not help appreciably.

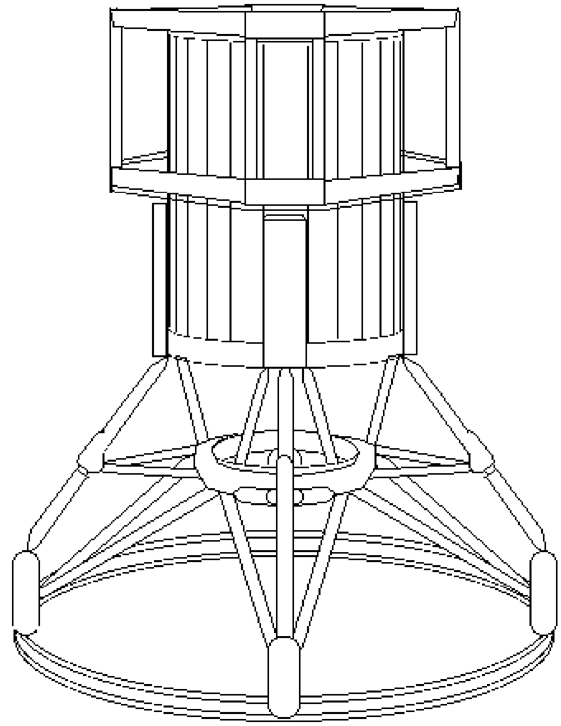

Fig. 6 - Grapple Assembly Concept Drawing

The grapple assembly requires several internal functions to be successful for this kind of mission, which make it similar to grapple assembly concepts developed earlier for exo-atmospheric transfer of payloads[10]. As a result of the relatively high rendezvous altitude of 100 km (330 kft), adding aerodynamic "lift" surfaces on the grapple assembly will not be effective in maneuvering the grapple toward a rendezvous with the hypersonic aircraft. The cylindrical portion of the grapple assembly will have a tether winch will allow the grapple assembly to "leave" its normal position at the end of the tether by letting out tether. The centrifugal force from the rotation of the tether can be used to "cast" the grapple assembly in toward the hypersonic vehicle before the Tether Central Station arrives overhead. The grapple assembly will have a reaction control system for fine control of its position, velocity, and orientation, but to minimize the problem of refueling of the grapple assembly, it will be up to the reaction control system on the hypersonic aircraft to remove most of the position and velocity errors during the rendezvous process.

The current concept is to fly the decelerating grapple vehicle in so that it approaches the hypersonic airplane from above and behind (this holds true for all grapple assembly designs considered). The attach ring would attach to the payload and pull the payload up to the grapple. The hypersonic vehicle would then return to ground and the grapple assembly, with payload, would be carried into space by the motion of the tether.

After the grapple assembly exits the atmosphere, the time spent in space will be used to cool and condition the grapple assembly, and recharge the batteries in preparation for the next aeropass. When the grapple assembly is not going to be used to capture or deploy a payload for long periods of time, the tether will be shortened by either the grapple tether winch, or one of the other winches along the tether, to raise the minimum altitude of the tether tip and keep the grapple assembly above most of the atmosphere.

The hypersonic grapple would not use externally mounted solar panel arrays during the aeropass due to the high aerodynamic forces and heating rates during this phase. Two options to supply electrical power to the grapple assembly have been identified: a deployable/storable photovoltaic array or an electrically conductive tether. Each would generate the required power, the latter while moving through the earth's magnetic field, and would store excess energy in the batteries for use during the aeropass phase.

In order to allow for a reliable rendezvous, the grapple vehicle must maintain location and attitude information and communicate with the hypersonic airplane. This can be done accurately with a differential GPS similar to those systems being developed for landing commercial aircraft. The approach velocities are too high to rely on human pilots on the ground so the system will require autonomous rendezvous and capture (AR&C) capabilities. AR&C technologies, such as advanced sensors for the final approach and rendezvous, are continuing to evolve, and are maturing based on Russian and NASA investments on docking technologies, and more recently, DARPA investments in the ASTRO refueling vehicle concept.

CONCLUSIONS

We have described a number of alternate system configurations that will allow hypersonic air-breathing airplane technologies to be combined with orbiting spinning space tether technologies to produce a method of moving payloads from the surface of the Earth into Earth orbit. The resultant Hypersonic Airplane Space Tether Orbital Launch (HASTOL) system is completely reusable and has the potential to drastically cut the cost of Earth-to-orbit space access. The system is revolutionary in that it minimizes, and perhaps even eliminates, the use of rockets for Earth-to-orbit launch of satellite payloads and even passengers.

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