Tethered Airfoils: An Enabling Technology

By Wayne German, WayneLGerman@Yahoo.Com October 22, 2003

1. Overview

Occasionally, new technologies are developed that meet global needs and generate considerable revenues in the process. Widely recognized examples are the light bulb, transistor, radio, television, computer, automobile, and airplane. The intent of this paper is to introduce another technology, Tethered Airfoils, whose *potential* to generate revenue exceeds all of these. The development, marketing, and deployment of this technology *could* yield the cheapest and cleanest means of: 1) electrical power generation, 2) shipping, 3) transportation, and 4) communication (radio signal relaying).

Each of these four areas could be revolutionized by the introduction of products that incorporate Tethered Airfoils. For the purpose of this paper, Tethered Airfoils are aerodynamically efficient inflatable kites in the shape of wings that have lift to drag ratios of ten to one or greater. Unless stated otherwise, they are extremely light when inflated with air and lighter-than-air when inflated with helium or hydrogen. These airfoils have on board power and autopilots for stable, remotely controllable flight. Most importantly, they provide a means of harnessing wind power to provide the mechanical power required to generate electricity, synthesize fuel, or provide propulsion.

2. The Potentials of Tethered Airfoil Technology

The potential applications for Tethered Airfoil technology are numerous. Some of the applications that should be possible are listed below. The applications that could most easily be developed are listed first followed by those that would require more skill and experience.

2.1. Wind power generators that use reciprocating airfoils to produce electricity on the ground.

2.2. Water pumps that use reciprocating airfoils to pump water for irrigation.

2.3. Sailing craft that have a Tethered Airfoil to tack into the wind or with the wind -- the airfoil being held aloft by aerodynamic lift, or buoyancy (helium or hydrogen), or both.

2.4. Recreational airships that fly over water without fuel by tacking in the air while being attached by tether to submerged hydrofoils.

2.5. Paraglider wings and ultralight aircraft that could use buoyant lift, and/or the methods of manufacture that are discussed in a separate paper entitled, Making Tethered Airfoils and Air Tensioners, would greatly reduce cost.

2.6. Passive self-regulation of altitude using highly pressurized lighter-than-air structures.

2.7. Ship and vessel propulsion assistance with minor retrofitting.

2.8. Energy conserving tugs that could deploy Tethered Airfoils to pull unmodified vessels across oceans.

2.9. Land Based High altitude wind power generators that use reciprocating Tethered Airfoils to tap winds as high as the jet stream to produce electricity at a generator on the ground.

2.10. Sea Based wind power generators (low or high altitude) to produce electricity at a boat or barge.

2.11. Synthesizing Hydrogen at Sea Using Tethered Airfoil Generators

2.12. Flight without fuel over land or water by using an airfoil at lower altitude tethered to another airfoil at a higher altitude to harness the power available in the differential velocities of the two altitudes.

2.13. Radio signal relaying by hovering indefinitely in the air while using excess wind to generate electricity to relay radio signals.

3. Conceptual Descriptions of Products Incorporating Tethered Airfoil Technology

3.1. Wind Power Generators

Wind power generating systems can be developed using reciprocating Tethered Airfoils. Using two airfoils and a tether that passes from one airfoil through an electrical generator on the ground to the other airfoil, power could be generated if one airfoil flew at a high angle of attack (nose up) while the other flew at a low angle of attack (nose into the wind or slightly down). The airfoil flying at a high angle of attack would have greater lift and drag, which would cause it to be blown downwind and upward while pulling the other airfoil upwind and downward. Electricity would be generated as the cable is pulled and the generator is forced to spin.

As the airfoil having the lower angle of attack approaches sufficiently close to the generator, remote control could cause it to assume a high angle of attack and cause the airfoil further downwind to assume a low angle of attack. This would cause the upwind airfoil to fly downwind and the downwind airfoil to fly upwind. Periodically changing the angles of attack would, therefore, cause the two airfoils to reciprocate in the sky producing power on the ground. Between strokes, as the airfoils change their angles of attack, and as the cable changes its direction of travel, there would be a brief time when no power would be generated. Therefore, in Tethered Airfoil wind farms the flights of all the airfoils should be synchronized so that as few as possible would change direction at the same time. This would ensure that the power generated at the farm would be as even and continuous as possible.

Note that only the pitch, or angle of attack, would have to be controlled remotely -- not the yaw and roll. This should make the design and development straightforward. Adjusting the tether bridle position fore and aft should provide the level of control required for this application. The Tethered Airfoil could be designed to passively correct for yaw and roll -- much the same way that single string kites do today.

A single Tethered Airfoil could produce electricity if a flywheel or external electrical power is used to winch the airfoil in on the upwind stroke. The airfoil would produce more power on the downwind stroke flying in a high lift, high drag mode than would be required to winch it back in on the upwind stroke.

The amount of power that a Tethered Airfoil could generate is not proportional to the size of the airfoil. It is proportional to the area swept by the airfoil per unit time -- just as in wind turbines. A small airfoil that quickly traverses a large area would generate more power. But Tethered Airfoils could generate far more power than wind turbines because they could sweep a greater area for an equivalent cost since they would not have the cost of the tower, nor be limited to the sizes that towers can accommodate.

Unlike standard wind turbines, Tethered Airfoils would not require expensive towers, specially designed low speed generators, and would not be subject to the strong vibrations that cause premature failures. Most importantly, they could fly at higher altitudes to harness more powerful winds. On average, over flat land, the wind is twice as powerful at every five-fold increase in altitude. So a Tethered Airfoil flying at only 500 feet would encounter twice the wind power as a wind turbine 100 feet off the ground. At a half mile the Tethered Airfoil would encounter more than four times as much wind power. This effect can be greatly magnified by terrain that causes the air to be funnelled -- as is generally found at the best wind farm sites.

Obviously, Tethered Airfoils that fly at high altitude would need to be assigned their own airspace a safe distance away from commercial flight paths. They might obtain permission to fly in the restricted airspace over wilderness areas because they do not pollute or make noise. Alternatively, the vast areas that exist offshore would provide excellent sites for both low and high altitude wind farming (as will be discussed) later. But initially, windy rural areas would provide good lower altitude proving grounds.

Inflated with helium, these Tethered Airfoils would simply float up in exceptionally calm winds. But in places, such as Minnesota, where the winds are constant and strong close to the ground it may prove practical to develop Tethered Airfoil Generators that rely exclusively on aerodynamic lift rather than buoyant lift. Inflated only with air, they could be developed to automatically launch from a stand when the winds blow sufficiently strong and be winched down quick enough to maintain controllable flight when the winds are exceptionally calm.

While the jet stream offers the greatest potential power per unit area, it may be more practical to fly larger Tethered Airfoils at lower altitudes. This would reduce the cost and drag of the tethers, but would require larger or more numerous airfoils to generate a like amount of power.

Even in typical installations, wind power used in conjunction with hydropower or fossil fuel plants could reduce the long-term rates at which these plants use water or fuel. These plants on the other hand, could provide backup power during periods of calm winds when these wind power generators would produce little or no power.

3.2. Water Pumps

Tethered Airfoils can be used to pump water as well as to generate electricity. The specific application of pumping water is mentioned here for three reasons. First, it would not require a generator. Pulling the tether could drive the pump directly. Second, water pumps do not require a consistent power source. If the winds cause short-term variations in the amount of water that is pumped there is no problem provided that daily or weekly quotas are met. Third, many nations require or could benefit by the use of good cheap water pumps.

Many underdeveloped nations need power to pump irrigation water. Studies conducted in Sri Lanka, Kenya, Cape Verda, and the Sudan show that windmills can be cost effective compared with diesel engines for pumping water. If windmills are considered cost effective, Tethered Airfoils should prove superior because they can extract power from much stronger winds and sweep through a far greater airspace. (As mentioned previously, the power that may be generated is proportional to the area swept per unit time).

3.3. Custom Sailing Craft

A lighter-than-air Tethered Airfoil and a watercraft having a small wetted surface could be tethered together to make a very fast and efficient sailing craft. Canoes and kayaks with centerboards or catamaran hulls would make good choices. Tethered Airfoils suitable for this purpose would need to have remotely controllable pitch and roll so that they could fly "out to the side" as well as downwind. These Tethered Airfoils would not require remotely controllable yaw. These airfoils could be designed (perhaps with a delta wing shape) to ensure that the Tethered Airfoil would always fly with nearly zero yaw with respect to the wind. (The purpose for flying "out to the side" is to generate a force perpendicular to the direction of the wind just as sails do when tacking into the wind.)

The Tethered Airfoils that have been discussed previously require pitch control only (nose up or down) The purpose of this control is to: 1) generate varying tether tensions by adjusting the lift and drag characteristics of these airfoils, or 2) to adjust the height of the Tethered Airfoils in the sky. Tethered Airfoils that could be used to provide propulsion into the wind (as well as with the wind) require roll control as well. These airfoils must be able to fly out to the side as well as overhead and downwind. The best Tethered Airfoil for this purpose would be one that could be directed to assume a relative position in the sky with respect to a hull -- in response to remote control -- and then hold that position indefinitely without requiring power. It appears that such control may be possible (and patentable).

A Tethered Airfoil should be able to passively maintain a new relative position in the air in response to a single radio control request to change the tether bridle position, flaps, wing warping, or center of gravity. Using this technique changing the attitude of the airfoil would cause the airfoil to select a different position in the sky. This, in turn, would cause the tether to be pulled in a different direction -- causing a new tack to be taken. If the airfoil could maintain this new position indefinitely after it had made these changes, it would be highly desirable, because power would only be required when changing tacks -- not to maintain the course of a tack. Even more important, is the fact that if it could passively self-correct it's own position it would be immune to brief system power failures or shutdowns. It would still continue to fly just as well on the same tack.

Members of the Flight Research Institute have demonstrated the feasibility of water skiing upwind or downwind with a Tethered Airfoil at the Columbia River Gorge. They also won first place in a speed sailing competition in England -- racing against craft having similar sail area. Even though the airfoil and hydrofoil were inefficient off-the-shelf kites and skis, they won by the greatest margin of the day.

While the principle of tacking into the wind with Tethered Airfoils may sound unique, it has actually been accomplished and documented as early as 1827 by G. Pocock. (The Samoans used it even earlier.) It appears that as soon as Orville and Wilbur Wright showed that it was possible to fly without a tether, virtually all scientific research into the applications of Tethered Airfoil flight ceased. Back then, the only way that an operator could remotely control a Tethered Airfoil, was by applying varying tensions on additional drag-inducing cables. The winds that kept the airfoil aloft also acted upon these control cables. When a wind gust would cause an airfoil to start diving to one side, different tensions would result in the control cables. Often, these different tensions would cause the airfoil to dive even more. These airfoils often flew out of control and crashed. What is surprising is that in 176 years nothing has changed.

To the best of my knowledge, no one has yet put an inexpensive autopilot and an aerodynamically efficient Tethered Airfoil together. I hope to work with others to be the first to achieve this goal. With such equipment there is no reason why Tethered Airfoils would not be every bit as stable, controllable, reliable, and useful as standard aircraft.

Tethered Airfoils could provide propulsion for small boats. Attached to the gunwales negligible listing moment would be generated. In fact, traveling with the wind, the airfoil could help pull the hull of smaller boats out of the water, thereby reducing drag. Motorboats, sailboats, hydrofoils, canoes, kayaks, sailboarders, skiers (both water and snow) -- all could be accommodated with a handful of different models. Unlike sails, Tethered Airfoils need not be custom made for each boat or application. No heavy masts, ballast, special ship design, or expensive retrofitting would be required. Like sails on a sailboat, Tethered Airfoils could provide power for all points of tack except dead into the wind. They would be better than sails because they would have an aerodynamically superior shape -- higher lift to drag ratios -- and therefore be able to tack much closer into the wind. They would also have access to the stronger winds aloft. They would have one cable, requiring one winch, and take up no deck space (mounted externally to a track on the gunwales).

Over land, the available wind power doubles with every five-fold increase in altitude. This factor can be much greater over water when the wind causes the waves to crest and the waves cause more pronounced boundary layer effects. So Tethered Airfoils could tap much more powerful winds than sails.

If a motorboat were outfitted with a Tethered Airfoil that flew at 500 feet (where the winds at sea are often three to four times as strong as at the top of most masts and towers) it could outrun most sailboats -- without engine power. Naturally, If the winds became too strong the airfoil could be tied down or deflated. For example, fishing fleets could race to their fishing grounds with their airfoils at high altitude and troll with their airfoils slightly overhead.

Motorboats under power could use Tethered Airfoils to provide a component of thrust in the direction they wished to travel. Suppose that a captain desired to travel east and decided to use an airfoil to help reduce fuel consumption. Suppose further that the wind was blowing such that his Tethered Airfoil pulled strongest in a northeasterly direction. He could accomplish his goal by directing the motors to cause an equally powerful thrust in a southeasterly direction. If the captain wished to travel east at 20 knots, the motors would only need to propel the boat at 14 knots. Depending on the ship and the sea conditions, this thirty percent reduction in motor propulsion speed could result in a fifty percent reduction in fuel consumption -- yet he could travel just as fast as if he had used motor power only.

It is typically reported that by assisting propulsion with standard sails, fuel consumption can be reduced by a fourth. But since Tethered Airfoils can harness winds having greater power, and since they could be much larger, Tethered Airfoils could save much more fuel. Since Tethered Airfoils could be attached at the gunwales they could never pull the boat over -- just along. So, unlike sails, Tethered Airfoils would never need to be furled to prevent capsizing. Tethered Airfoils should always be able to make use of the best winds -- at altitudes where there is over four times as much power available.

The Tethered Airfoils for sailing applications could be inflated with lighter-than-air gases such as helium or hydrogen so that they would simply float up in exceptionally calm winds. Alternatively, they could be inflated with air in which case they would need to launch and land as the winds would permit. As the winds would become strong enough, or as a boat having a propulsion source would pull, an air inflated Tethered Airfoil could be launched by letting out the tether. To land the airfoil when desired, or in the event of exceptionally calm winds, a winch could pull the Tether back in again at a sufficient velocity to maintain stable flight.

Airfoils that are inflated with air would be advantageous because they could readily be deflated and conveniently stored on board when not in use. Also, there is additional cost and logistics involved in obtaining, storing, and transferring lighter-than-air gases. As elegant as it would be to have lighter-than-air Tethered Airfoils pull boats, in general it would probably be more practical to use air inflated Tethered Airfoils.

3.4. Recreational Airships that Fly Over Water without Fuel

As soon as Tethered Airfoils are developed that can pull hydrofoils reliably, passengers could fly in gondolas attached to airfoils rather than sail in hulls over the water. The principles of operation would be just the same. The only difference is that the hydrofoil would now be remotely controlled rather than the airfoil. Such a craft should have a much smoother ride. The tether would dampen Wave action before it was transmitted to the gondola. In the event that the wind stopped, the gondola would simply float -- being held up by the buoyant lift of the lighter-than-air airfoil.

This configuration could render a truly efficient sailing craft because a lighter-than-air airfoil could support the passengers, cargo, and all other components of the craft except for the hydrofoil that would be required for tacking. In other words, the craft could be made very efficient by the elimination of the hull and all unnecessary water drag. Having a high sail, very little drag, and always being "up on the hydrofoils" such a craft could sail even in the lightest of winds. For truly high speed, the airfoil could fly at high altitudes. For passenger comfort without cabin pressurization, the gondola could be attached to the tether a reasonable distance above the ocean.

Nearly this same level of comfort and efficiency could be obtained by using Tethered Airfoils that are inflated with air. In this case, the Tethered Airfoil and gondola would have to launch and land as the winds would permit. But this would probably not be a very big penalty because they would land when the winds would provide little or no propulsion and when the water would be calm. The one disadvantage in using air rather a lighter-than-air gas to inflate the airfoil is that some of the aerodynamic and hydrodynamic lift generated by the airfoil and hydrofoil would have to be used to lift the gondola and wing. Normally, a relatively small percentage of the power would be required to lift the gondola and wing. The vast majority of the power would still be available to provide propulsion.

As the winds would start to pick up, this craft could be launched by releasing tether from a spool in the hydrofoil. In many cases this would be sufficient to cause the gondola and wing to take to the air. But if the winds at low altitude were insufficient, the gondola and the airfoil would float on the water downwind from the hydrofoil. When the tether would be let out sufficiently, the tether could be winched back in briefly and strongly to cause enough tension in the tether between the hydrofoil and the airfoil to pull the airfoil into the sky. Once in the sky, under the influence of greater wind power, the winch could stop pulling and gradually let out more tether so that the gondola and airfoil could ascend to the altitudes that would allow tacking.

3.5. Paraglider Wings and Ultralight Aircraft

Tethered Airfoil construction techniques should enable the construction of high performance inflatable paraglider wings and ultralight aircraft. Standard Paraglider wings are ram-air inflated. This causes drag to be generated at the leading edge. Also during flight, standard paraglider wings can easily be deformed into less efficient shapes. Tethered Airfoils should be at least as light, but they should form much more rigid and well-defined airfoil shapes. It should also be possible to use these techniques to make inflatable ultralight aircraft.

3.6. Passive Self-Regulation of Altitude

Using the proprietary construction methods that are discussed in the paper “Making Tethered Airfoils and Air Tensioners”, highly pressurized lighter-than-air airships (airfoils, aircraft, or balloons) could be manufactured that could passively stabilize their altitudes in free flight without being restrained by tethers. These construction methods could be used to make lighter-than-air airships that would prevent the internal gases from expanding as they rise. These would be constant volume airships. As a consequence, if they were free to ascend or descend they would come to rest at the altitude that would have the same density as the over-all airship. If these balloons rose higher -- perhaps due to momentary gusts -- they would be heavier than the surrounding air so they would settle back down. Likewise, if they were lower, they would be lighter than the surrounding air so they would rise. They would always passively return to the altitude whose density is equal to that of the airship. In short, they would require no monitoring, control, or power to automatically self-regulate their own altitudes. If they were in no hurry they could float to destinations downwind consuming no power. This might be a useful plan in hauling freight inexpensively.

This technique was used by NASA in the Ultra Long Duration Balloon that launched March 16, 2003, and which was designed to circumnavigate the globe for 100 days. Interestingly, this technique has never been used to maintain the altitude of lighter-than-air man-lifting balloons or airships.

To date, all lighter-than-air man-lifting balloons require continual monitoring and adjustments of altitude. This is because the air in these balloons expand during ascent and compress during decent. If they start upward, they continue upward at an accelerating rate, until helium is released to cause them to descend again to the desired height. But once they start to descend they continue to descend at an accelerating rate, until ballast is released to cause them to ascend again. These balloons continually rise and fall requiring continual releases of helium and ballast to compensate.

In standard airships or blimps, the lifting gas is free to expand or compress to come to equilibrium with the surrounding air. So as the airship descends, the gases compress. This would cause the airship envelope to become limp were it not for ballonets. Ballonets are special internal air pressure compensating balloons that inflate during descents to maintain a small but uniform positive pressure in the airship. Unfortunately, a ballonet requires a fan to maintain a slight positive pressure. The fan in turn requires a power source. Present day airships do not regulate altitude by alternately releasing helium and ballast like balloons. That would be too costly. Instead, they use the aerodynamic forces of thrusters to maintain altitudes when the airship has a different density than the surrounding air. These thrusters are used to provide an upward force when the airship is heavier than the surrounding air and a downward force when the airship is lighter. This method requires engines that continually consume fuel.

It would be better if airships were designed to withstand high internal pressures (such as up to 5 psi). To ascend, air could be released from an internal ballonet. The loss of this air, and the expansion of the helium that would result in the adjacent chambers, would lower the overall density of the airship, which would cause it to rise to the altitude having the same density -- and no higher. To descend, a compressor would be required to draw air back into the ballonet. This additional air, and the compression of the helium that would result, would cause the airship to descend to the altitude that would have the same density -- and no lower.

Such an airship would never need to discard helium or ballast, or consume fuel to maintain a specific altitude. It could also be smaller because it would not need the extra buoyancy required to lift ballast or the additional fuel required to maintain altitude. In the course of adjusting altitude, this airship would only need to consume power when using the compressor to draw in additional air to descend. It would require no power to maintain a specific altitude or ascend. It could float indefinitely downwind at a specific altitude without requiring any altitude monitoring or control.

3.7. Ship and Vessel Propulsion Assistance

If freighters and ocean going vessels used even relatively simple and inefficient Tethered Airfoils they could realize dramatic reductions in the costs of fuel. When traveling the direction that the jetstream blows (eastward in the Northern Hemisphere) the vessels could pull large Tethered Airfoils into the jetstream. Once in the jetstream, these airfoils could simply pull the vessels downwind. A 50 percent reduction in the cost of fuel one direction on a large freighter would save hundreds of thousands of dollars annually. Efficient Tethered Airfoils might be able to save significantly more because they could provide propulsion assistance on the return upwind trip as well.

Some freighters have been designed to use metal sails to provide propulsion assistance with the wind or into the wind. They are designed to save as much as 60 percent of the cost of the fuel. Like all sails, these metal sails cause the vessels to list to one side when the winds blow. Listing causes all decks and cargo bays to have sloping floors. To prevent capsizing, the metal sails are "furled" by folding. They require special ship designs to accommodate the masts, ballasts, and the forces that the sails generate.

Tethered Airfoils in contrast could provide greater power from higher altitudes and yet cause negligible listing. Little or no retrofitting would be required because Tethered Airfoils could pull the vessels at the same attachment points that tugs would use. Even if these Tethered Airfoils were not lighter-than-air they could be self-launched into the apparent wind generated by these ships at sail.

Between territorial waters there are no governmental bodies that regulate how high Tethered Airfoils would be allowed to fly. As low as a ten percent reduction in the worldwide consumption of fuel by freighters would save billions of dollars annually -- not to mention the environmental benefit of reduced pollution and less global warming.

3.8. Energy Conserving Tugs

Special tugs could be designed for the express purpose of manipulating Tethered Airfoils to pull ships across oceans. This would have the advantage that the large vessels would not have to manipulate the Tethered Airfoils directly. All the tasks associated with providing propulsion assistance could be handled by a tug specially designed to do the job. Tethered Airfoils suitable for this purpose would probably not have to be lighter-than-air. The tug could sail into the wind, pulling even a heavier Tethered Airfoil into the air. A heavier-than-air airfoil would have to fly exclusively by aerodynamic lift, but it could still land safely even in calm winds by being pulled in fast enough to ensure stable flight back down.

3.9. Land Based High Altitude Wind Power Generators

Most appealing is the prospect of harnessing winds in the jetstream where the wind power is often hundreds of times greater than at the top of masts and towers. Technical and political hurdles would have to be overcome, but as Tethered Airfoil technology matures and gains acceptance jetstream wind farming may prove practical.

At each site, the local terrain and the proximity to the jetstream will determine whether it would be best to fly more airfoils at lower altitude or fewer airfoils at higher altitude. Mountains or other land formations that funnel wind may favor lower altitudes. One such mountain range exists in Hawaii. This range runs perpendicular to the prevailing winds and funnels winds up and over. (Hawaii also has expensive electricity and a state government that has recently invested millions in wind energy development in a single year.)

Obviously, Tethered Airfoils that fly at high altitude would need to be assigned their own airspace. They could be assigned airspace far from the commercial flight paths. In rural Kansas, for example, strong constant winds at ground level would assure that the Tethered Airfoils could self-launch and self-land inflated only with air. Alternatively, they might obtain permission to fly in the restricted airspace over wilderness areas because they do not pollute or make noise.

Many Third World countries are crossed by the jet streams of the northern and southern hemispheres. They might desire to relinquish airspace to produce inexpensive electrical power. If the winds at ground level are insufficient to launch these Tethered Airfoils, they could be filled with helium or hydrogen so they would always be in flight even in calm winds.

(Ever since the Hindenburg blew up, people have been reluctant to use hydrogen in lighter-than-air aircraft, but it should be noted that the Hindenburg contained the hydrogen in "gold beater's skin" -- the intestines of calves beaten thin -- nothing to be compared with today's multi-layered plastic films.)

A number of articles have been written about the feasibility of developing wind power generating systems that could tap the power of the jetstream. But the systems described in these research papers consist of wind turbines mounted on large metal wings that are tethered with special power conducting cables. The wings use the turbines as thrusters for launching and landing. The complexity and manufacturing costs are staggering; yet the amortized costs of the electrical power generation are considered favorable (in the 7.5 - 9.5 cent per kilowatt range nearly twenty five years ago).

However, it would be much simpler and less expensive to design a system that would:

1) Have an ordinary land based generator,
2) Have inexpensive inflatable fabrics that can be quickly deflated and stored away during periods of excessive wind,
4) Bounce rather than crash in an accident,
5) Contain virtually no costly and fragile high tech components,
6) Require no heavy turbines or metal cables to conduct lightning,
7) Never need to land during light winds,
8) Provide a much greater return on investment because the same costs could be used to construct larger Tethered Airfoils that could extract power from a greater area.

Over much of the United States the average potential power of the air that flows through one square meter of the jet stream exceeds 10 kilowatts. Drag on the tether and airfoil(s) will, of course, limit how much of this potential power can be converted into mechanical or electrical power. Greater potential exists over Maine where during a winter month (when the need for power is greatest) the average power available per square meter exceeds 30 kilowatts (or 40 horsepower). The greatest wind power in the world is found near Tokyo Japan where the average power exceeds 60 kilowatts (or 80 horsepower) per square meter in the winter.

As stated before, the power generated would be proportional to the area swept by the airfoil per unit time, so if a Tethered Airfoil the size of a soccer goal (8’ x 24’) were to fly in the jet stream near Tokyo, and if it quickly swept an area ten times as large and was 20 percent efficient over all, it would generate 2.14 Megawatts of electricity. The efficiency is conservatively assumed to be very low to account for the weight and the drag of the tether and the fact that wind turbines are only 60 percent efficient at best. But in practice, it is expected that the efficiencies and the power generated could be significantly greater. Even so, at 10 cents per kilowatt-hour, very modest by Japanese standards, and assuming an average power of 40 kilowatts per square meter, this single small airfoil could generate a gross revenue of $1.25 million dollars annually.

Japan has expensive electricity and no indigenous fuel supply. It has few hydroelectric facilities and little land to set aside for solar power generators or wind turbines. The people of Japan fear nuclear power due to the bombing at Hiroshima and a near catastrophic accident at one of their nuclear plants. So harvesting the power in the winds offshore and/or in the jet stream may be the most desirable means of generating electricity for their nation.

3.10. Sea Based High Altitude Wind Power Generators

Studies have pointed out the potential of generating electrical power using wind turbines at sea. A major expense outlined in these studies is the cost of installing and maintaining the stationary platforms and towers required to hold the turbines in the air. Tethered Airfoils do not require tall towers or large platforms. Instead, small boats or barges could contain generators and be able to automatically launch, coordinate the flights, and retrieve the airfoils. Since the winds at sea are generally strong, these airfoils could fly totally by aerodynamic lift, so they would not require lighter-than-air gases. Using the methods of manufacturing that are discussed in the paper “Making

Tethered Airfoils and Air Tensioners", these airfoils could momentarily bend and deform in the heaviest winds -- rather than break and fracture.

Since these Tethered Airfoils could fly as high as the jet stream, where the wind power is often 30 to 100 times as great, and since they would not require tall towers or large platforms, and since they could be made with inexpensive fabrics and low tech components, the cost of the power that the Tethered Airfoils could produce should be much less. Within 200 miles of shore both ocean and airspace would have to be reserved, but permission to reserve this space should not be difficult to obtain because Tethered Airfoils do not pollute or make noise and they could not easily damage people or property at sea if they are assigned their own space. More than 200 miles offshore, outside of territorial boundaries, they could fly without obtaining permission from anyone. In fact, with limited taxation (or no taxation in the case of Liberian registry), and no property cost -- save for a power cable right-of-way connecting the wind farm to the land, this might be the most cost effective alternative. (Lights, radar, and automated radio warning systems could warn approaching craft.)

3.11 Synthesizing Hydrogen at Sea

There is a method of generating electricity from the winds at sea that would not require power cables to transmit the electricity to land. In this case, boats at anchor or sailing the seas could deploy reciprocating Tethered Airfoils. The electricity generated could be used to electrolyze seawater to generate hydrogen that could be stored in onboard tanks. Later these tanks could be transferred to power stations where fuel cells or conventional steam turbines could use the hydrogen to generate electricity. Therefore, boats could ply the waters off countries such as Japan to harvest wind power for the purpose of synthesizing hydrogen to sell: 1) to local power stations to generate electricity, or 2) as an automobile fuel.

Not all of the electrical power that is used to synthesize hydrogen can be reclaimed when the hydrogen is used to generate electricity again. These processes are not a hundred percent efficient. Also, the storage and transportation of hydrogen presents other difficulties. So it will always cost more to synthesize, store, and transport hydrogen than use wind generated electricity directly. But hydrogen is the cleanest fuel of all. When hydrogen is used to generate electricity the output "exhaust" is pure water. Utilities pay a premium for electricity that is generated without producing pollutants. More importantly, electricity that is stored in the form of hydrogen can be converted back to electricity at times of peak demand when electricity can sell for over three times as much as it normally does. So, all of the costs associated with converting electricity to hydrogen and back again can be more than offset by selling the electricity at times of peak demand. Moreover, the conversion of wind power to hydrogen to electrical power could provide backup power during periods of calm winds for other Tethered Airfoils that provide more efficient direct power.

Wildcat oil miners risk much every time they attempt to sink a new hole at sea. Each hole could come up dry or cause much pollution. Sea based Tethered Airfoil wind farmers would risk much less and would have a resource that would never run out. The main risk in developing sea based wind power generating systems is the risk incurred in developing the first one. After the methods of manufacture and deployment are resolved, there is never a chance of finding a "dry hole". The patterns of the jetstream are well known. In the United States, the owners of Tethered Airfoil wind power generating systems have another benefit: power companies are obligated to buy the power produced by private individuals or companies at fair market rates. Having an obligated customer means that this enterprise should be recession or depression proof. Wildcat oil miners, in contrast, have no such benefit.

3.12 Flight without Fuel

Actually, there is not any reason why anything must drag through the water or be attached to the land in order to make a system that can tack using airfoils. Two airfoils attached to opposite ends of the same tether can accomplish the same thing. If one airfoil is in faster moving air at a higher altitude and the other airfoil is in slower moving air at a lower altitude, then the craft can tack. The principle is the same as an airfoil attached to a hydrofoil. The only difference is that instead of using a hydrofoil in the slow moving water, another airfoil could be used as in the slow moving air.

If a passenger-containing gondola were attached to the lower of the two airfoils, then the upper airfoil could ascend into the jetstream for fast, silent flight. This aircraft would require a sophisticated autopilot because it could tack vertically as well as horizontally. Fortunately, low cost microprocessors and servomechanisms can be developed that can perform all flight operations with little or no human intervention. As an example, autopilots could be pre-programmed to fly between any two points on earth using sensors that receive information from the Global Positioning System (GPS). Using these sensors (and others) the airfoils could continuously monitor their exact positions above the earth (to within a few meters), their attitudes (pitch, yaw, and roll) and the wind velocity and direction. With this information, the autopilots could cause the airfoils to automatically launch (causing the mooring cable to become disconnected from the ground) fly to a pre-programmed destination using a pre-determined route, then dock at a destination (flying the mooring cable such that the ground end is caught by a waiting receptacle).

In June of 1982, the Smithsonian magazine had an article that stated: "A kite flying across the wind will fly faster than the speed of the wind. If the lift-to-drag ratio is ten to one, the kite theoretically can go ten times as fast as the velocity of the wind." This article also stated: "The wind blows hardest (more than 100 miles per hour) about 30,000 feet above the ground in the jet stream." Taken together, these two facts would suggest that Tethered Airfoil airships could fly faster than 1000 miles per hour in the jet stream! This is impressive but not realistic. At these speeds the long tether would have considerable drag. Furthermore, flying crosswind means that the craft would be restricted to flying in specific directions. If the average practical speed (due to limitations of tether length and drag) were only 20 percent of this theoretical maximum, if it were no greater than 200 miles per hour, it would still be highly desirable because it would be flying without fuel.

Since these airships would consume no fuel, they could prove very competitive as haulers of airfreight, low cost air transportation, pleasure craft, or sightseeing craft. They would not need airports. Moored to the ground as aerodynamically shaped helium filled kite-balloons, and perhaps using thrusters to help maintain position, they could load and unload people or cargo from open areas or the flat roofs of large buildings. In the days of the old airships it was said that: "You can fly in an airplane, or you can voyage in a Zeppelin". Zeppelins of those days had ballrooms and verandas in the sky. There is no reason why these newer airships could not be at least as gracious.

Since there is generally a large differential in velocities between the winds in the jetstream and those just below, if the cabin were pressurized, and the lower airfoil was below the jetstream, the tether required for free flight could be made much shorter -- thereby reducing drag, increasing speed, and freeing more airspace. A commercial version of this airship could have metalized plastics for the retention of lighter-than-air gases and for good visual and radar tracking.

3.13 Radio Signal Relaying

When it becomes possible to fly indefinitely by tacking in the air (as was just described), it should be even easier to tack in order to stay in the same general location. When this feat is achieved it could lead to the cheapest means of communication. Small wind turbines could generate on-board power that could be backed up by battery to provide a consistent power source

24 hours a day. This form of hovering would not require the same aerodynamic efficiency as a craft designed to tack to locations upwind. Therefore, the on-board wind turbine should not restrict operation. Such wind turbines would introduce drag. But if the objective were to maintain position rather than to progress to locations upwind, some additional drag could be accommodated.

Already, nations have expressed concern that there may not be enough locations above the equator at which to position all the geosynchronous communication satellites that the world may shortly need. It should be far cheaper to make geosynchronous craft that can tack in the air without fuel. They would not need to be positioned above the equator and they could launch and land under their own power wheneve maintenance would be required. Just a few of these flying high in the jet stream could provide a network that could provide continental coverage. They could provide the cheapest means of mass communication.

Recently an aircraft named Helios demonstrated that it is possible to fly at high altitude by the power harvested by solar cells alone. This is a very technically complex craft. By contrast a Tethered Airfoil craft could accomplish this feat with two simple inflated craft tethered together. It would not be restricted by the availability of sunlight.

3.13 In-Flight Generation of Fuel

If it proves to be possible to tack in the air while generating power from on-board wind turbines, commercial wind power generators could be developed using this concept. By tacking "in place" in the jet stream they could generate electricity with which to produce hydrogen from water. Afterward, these craft could fly to power generating stations that could use fuel cells to generate electricity from the hydrogen, generating no pollution aside from water vapor. Alternatively, the hydrogen could be sold as a non-polluting automobile fuel.

4. The Initial Objectives of Tethered Airfoil Research and Development

Currently, the support and endorsements for the development and commercialization of Tethered Airfoil Technology are fairly balanced between those who would want to see it initially used to generate electricity and those who would want to see it initially used to propel efficient sailing and flying craft. Each has their relative merits. Electrical generators would have to overcome more political hurdles if they fly at high altitudes, but sailing and flying craft would present more technical challenges. Electrical generators might provide a greater income long term, but sailing and flying applications would probably find more immediate acceptance. In either case, the Tethered Airfoils that would be best suited to these tasks would be airfoils that could maintain their relative positions in the sky with respect to their mooring sites – positions that could be specified, and could be changeable, by remote control. In other words, the best Tethered Airfoils for these applications would be ones that could be programmed by remote control to fly to specific locations left, right, up, or down in any wind. These airfoils should maintain nearly constant position until programmed to move to another position. Lastly, they should consume as little power as possible to stay in a programmed position.

Typical kites stay in position without consuming power, but they cannot maintain position to the left or right of their mooring location. The goal here would be to develop Tethered Airfoils that could stay in any programmed position in the sky that kites could reasonably fly in. These airfoils would require an autopilot, remote control electronics, and servomechanisms. These are areas that I would feel confortable developing. What I need is help developing the best control theories and mechanisms to maintain position at the lowest possible inflight power consumption. But the first goal is to demonstrate a practical method of being able to manufacture these Tethered Airfoils quickly and economically. It is for this reason that the objective of this initial unsolicited proposal is to obtain funds to plan the development of a system that could be used to manufacture Tethered Airfoils. The proposal, itself, is near the end of this paper.

6. Tethered Airfoil Generators Compared to Other Power Generating Technologies

All of the current and proposed methods of energy generation or fuel synthesis have their advantages and disadvantages. Below the costs of consuming oil are discussed. Afterward, the advantages of Tethered Airfoil Generators are discussed and compared against the current and proposed methods of energy generation. The intent is to lay a foundation that will clearly establish our need for a cleaner, safer, cheaper source of power other than that, which is currently available or proposed.

6.1. The Hidden Costs in Oil Consumption

According to the US Geological Survey (the branch of the government that assesses oil reserves) virtually all of the oil that is known to exist or is likely to be discovered in the United States will be consumed within the next twenty five years. Currently, oil is cheap and abundant, yet the purchase of foreign oil is the single biggest contributor to our spiraling trade deficit and global indebtedness. When oil is no longer abundant it will no longer be cheap -- in which case our trade deficit and indebtedness will likely soar.

Even in peacetime we spend considerable sums just to secure access to Mideast oil. According to an article in the April 1991 issue of Scientific American, it is estimated that the Pentagon has spent between 15 and 54 billion dollars annually to secure access to Mideast oil – even before the fitrst war in Iraq. As long as we are dependent upon the consumption of foreign oil we will continue to spend much money securing access to the oil and safeguarding the remaining reserves.

In times of war we spend much more. In the heart of an oil glut we fought the first war in Iraq to secure access to oil. A quarter of a million Iraqis died and over 60 billion dollars was spent by the allied forces alone. Shouldn't we expect that when global oil supplies diminish such wars would become more common and widespread? Already, Middle Eastern nations such as Iran are arming themselves to exert regional authority and to prepare for such conflicts -- this time with nuclear weapons. The point is simple: our need for foreign oil compels us to spend considerable sums to ensure our access to oil in peace time and to fight wars when that access is threatened.

Perhaps most importantly, the consumption of oil or other fossil fuels degrades the environment through smog, acid rain, the green house effect, and inevitable wide spread accidents such as oil tanker spills. Millions suffer and many die from respiratory illnesses, entire forests are being decimated, and vast stretches of ocean are being laid waste. According to the article in Scientific American, it is estimated that at the current rate of oil consumption the environmental degradation, increased health care, lost employment, and other factors cost the United States between 100 to 300 billion dollars annually -- not to mention the 15 to 54 billion dollars that the pentagon spends in peace time to secure access to Mideast oil -- nor the costs of fighting wars to secure access to oil such as in Iraq. These "hidden" costs are in addition to the prices paid at gas pumps. World wide these incidental costs may exceed one trillion dollars annually. The world pays an enormous price to consume oil -- politically, economically, and environmentally.

6.2. Comparing Tethered Airfoil Electricity Generation and the Solar Power

Solar power has long been promoted as an energy source that is likely to be used to meet much of the future demand for power. Advocates of solar power point out that it is clean, dependable, and uses a renewable energy source. While true, all of these claims can be made for Tethered Airfoils Wind Power Generators as well.

Compared to solar energy sources, Tethered Airfoil Generators:

6.2.1. do not require expensive and inefficient energy storage and retrieval systems to convert daytime power into nighttime electricity,

6.2.2. do not require much sun-favored land since they can share land with agriculture (or go offshore to avoid the use of land altogether),

6.2.3. can efficiently generate power at far more sites throughout the world (such as anywhere under the jet streams of the northern and southern hemispheres or over the oceans where the installation of solar cell arrays would be impractical, if not impossible),

6.2.4. can extract energy from a source that is hundreds of times more powerful per unit area (10 kilowatts per square meter is often the average power available in winds in the jet stream versus 100 watts of solar power per square meter), and

6.2.5. are more efficient at extracting power (even windmills are generally more than four times as efficient as solar cells in extracting power)

6.2.6. could offer a greater return on investment by generating more power at less cost.

In short, Tethered Airfoils hold greater promise for economical and ecological power generation than solar cells.

6.3. The Wind Turbine Alternative

Currently wind turbines offer the most practical and cost effective means of generating electricity from a renewable energy source, but Tethered Airfoil Wind Power Generators promise to offer a much more cost effective solution. Wind Turbines will probably always be more efficient, but Tethered Airfoil Generators should be much less expensive to install and maintain when generating equal power.

Unlike standard wind turbines, Tethered Airfoil Generators would not require:

6.3.1. towers,

6.3.2. stationary platforms,

6.3.3. rigid, fragile blades,

6.3.4. airfoil sizes to be limited to the strengths of the towers,

6.3.5. expensive custom low speed generators,

6.3.6. operation in the slow and variable winds close to the earth, or

6.3.7. land.

Tethered Airfoil Generators could use standard generators. Since they would have no rotating blades they would not be subject to the strong vibrations and torsional forces that have caused many wind turbines to fail. They would be constructed of inflatable fabrics rather than rigid materials so they would bend and deform in excessive winds rather than fracture and break. Most importantly, they could fly at higher altitudes where the winds are stronger and more constant.

Generally over level terrain the velocity of the wind varies in relation to the elevation above ground by the "one seventh power law":

velocity_high / velocity_low = (elevation_high / elevation_low) ^ (1 / 7)

The power available in the wind is proportional to the cube of the velocity, so over level terrain the power in the wind varies in relation to the elevation above ground by the "three sevenths power law":

power_high / power_low = (elevation_high / elevation_low) ^ (3 / 7)

From this equation comes the simple relationship that winds that are 5 times higher are very nearly twice as powerful. Similarly, winds that are 25 times higher are 4 times more powerful. Thus, if Tethered Airfoils were to fly just a half mile in the air above standard level terrain they should encounter winds that would be over 4 times more powerful than the winds encountered by turbines that were 30 meters (nearly 100 feet) above ground -- and over 6.5 times more powerful than turbines at 10 meters (nearly 33 feet). These comparisons are for winds above level terrain -- the general case. Near mountain ridges, and other places where the terrain funnels the air, the power available can increase far more with changes in height. Likewise, at sea, when strong breezes blow, the power available in the winds varies more markedly with changes in altitude. This is because strong breezes make waves that effectively slow the winds closer to the earth even more -- which causes a greater change in velocity with height.

The purpose of these discussions is to show that Tethered Airfoils could tap into winds that are much stronger than those accessible by commercial wind turbines -- even if the Tethered Airfoils were to fly relatively low. But as the technology progresses, and as it becomes practical to fly as high as the jet stream, then Tethered Airfoils could tap into winds that can be hundreds of times more powerful.

Besides being able to tap into much stronger winds, Tethered Airfoils could also be more practically constructed and deployed in larger sizes. This would allow them to extract power from a greater area. Compared to wind turbines, Tethered Airfoils would be more practical to scale up to larger sizes for two reasons: 1) Within reasonable limits, key materials are more economically manufactured, more readily available, and easier to manipulate in larger sizes, and 2) Tethered Airfoils would not have to be limited to the sizes that towers can accommodate.

If wind turbine towers were made twice as tall then the blades could be twice as long, and the turbine could extract power from an area four times as great. But the tower could require 16 times as much material (and cost) to accommodate the greater load at the increased height. This simple example shows the strict size limitations that towers impose on wind turbines. Tethered Airfoils, on the other hand, have no tower and would channel all the force that they would generate directly to a generator located on the ground.

7. The Advantages of Constructing Tethered Airfoils of Larger Size

For nearly all of these applications, the economies of scale should favor Tethered Airfoils of larger size. If the linear dimensions (length, width, and height) of a Tethered Airfoil were all to double, then the volume and buoyant lifting forces would increase by a factor of eight. Such an airfoil could support eight times as much payload during periods of <u>calm wind</u> -- without requiring the use of a stronger tether. The payload or ballast of this airfoil could be adjusted to offset the increases in buoyancy, so the tether would not have to increase in strength to support the greater <u>buoyant forces</u>.

If the linear dimensions of a Tethered Airfoil doubled, then the surface area, aerodynamic lifting forces, and tether tensions would increase by a factor of four. This would necessitate the use of a tether that is four times stronger, has a diameter twice as large, and a drag about 2.5 times greater. (Tether drag increases faster than the diameter and less than the cross-sectional area.) Therefore, <u>when the tether is the predominant source of drag and when buoyant lift is small compared to aerodynamic lift</u> (as should normally be the case), each time the linear dimensions are doubled, the overall lift-to-drag increases by a factor of 1.6. In other words, if a Tethered Airfoil had an overall lift-to-drag ratio of 5.0, then doubling it's linear dimensions would yield a lift-to-drag ratio of 8.0. The point is, that larger Tethered Airfoils are more efficient. This means that craft that use larger Tethered Airfoils could travel faster and closer into the wind. Likewise, Tethered Airfoil Wind Power Generators that use larger Tethered Airfoils could fly higher, tapping into winds that are more powerful, or they could fly at the same altitudes with a shorter tether since the tether could be more vertical. In these applications, the increased buoyancy would best be used to provide additional lift so that the airfoil could fly still higher using even less tether. (It is assumed that the aerodynamic lift would still be much larger than the buoyant lift so a stronger tether would not be required to support the additional tension due to bouyancy.)

Perhaps, the greatest advantage in increasing Tethered Airfoil size is that the materials that are proposed for Tethered Airfoil manufacture are more readily available and economically produced in larger sizes. Using proprietary construction techniques, larger airfoils would be easier to manufacture (within limits) and more aerodynamically refined and efficient -- again leading to higher lift-to-drag ratios, faster speeds, and higher altitudes with less tether.

8. Technical Endorsements

Many of the ideas that are disclosed in this paper have been reviewed by some of the most widely recognized authorities on aerodynamics and hydrodynamics:

8.1. Bernard Smith, the Retired Technical Director of the Naval Weapons Laboratory, has been a pioneer in the integration of airfoils with hydrofoils to make efficient sailing craft. When he reviewed an early draft of these concepts he pointed out a few inaccuracies and yet wrote:

"Your paper has enough good ideas in it to be worth the effort required to perfect it".

8.2. Later, a revised paper that describes these ideas was sent to the Flight Research Institute (FRI) for their evaluation. (The FRI was a non-profit experimental offshoot of Boeing Commercial Aircraft.) After reading the paper, Jack Wimpress, the Retired Chief of Product Development at Boeing, and Harry Higgins, a Retired Engineering Supervisor, thought that the potential to generate electricity with reciprocating Tethered Airfoils appeared promising. They invited me to pursue this technology as an Associate Project Leader under the auspices of the Flight Research Institute (FRI) and offered their assistance and guidance (which is gratefully acknowledged!).

They wrote a letter of endorsement concerning Tethered Airfoil Wind Power Generators that says:

"As a result of our studies of your invention we have concluded that your concept is fundamentally sound and we believe that your goals can be achieved by step-by-step demonstrations and that each step can be accomplished within a reasonable effort."

Later they reconfirmed their willingness to provide assistance:

"We plan to continue our support of the Project in the areas of technical guidance and account monitoring as we are able and as long as such efforts will help you attain our goals. Be advised that we are able to call on professional support from both the University of Washington and the Boeing Company in support of this work."

To summarize then, the Flight Research Institute offered to assist the Tethered Airfoil Development Project three ways: 1) by providing free technical consultations and monitoring of project finances by some of the most widely respected aeronautical design engineers and managers of aeronautical development, 2) by providing free access to the best aeronautical design and development computers at Boeing, and 3) by providing tax deductions for money invested in development.

8.3. Reiner Descher, a professor of aeronautics at the University of Washington liked the concept of using lighter-than-air airfoils in conjunction with hydrofoils to make efficient sailing craft -- and perhaps also to pull freighters. He said he would like to supervise at least one graduate student who would spend a year technically and thoroughly evaluating these proposals. We hope to find the funding required to support this work.

Not too surprisingly, these three evaluators and endorsers have differing opinions regarding which implementations of this technology should prove to be most practical and profitable, and which should be pursued first. Smith, for example, believes that Tethered Airfoils could be used as a means to pull freighters. Wimpress and Higgins are more skeptical about this application and would rather not offer their support to pursue this objective initially. Descher, on the other hand, believes that it might be possible to design around the technical limitations that Wimpress and Higgins foresee. Also, Wimpress, and Higgins see more potential in the development of Tethered Airfoil Wind Power Generators than Smith.

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