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HUMAN POWER

THE JOURNAL OF THE IHPVA ISSUE NO. 12 Vol. 3, no. 3 SPRING 1985

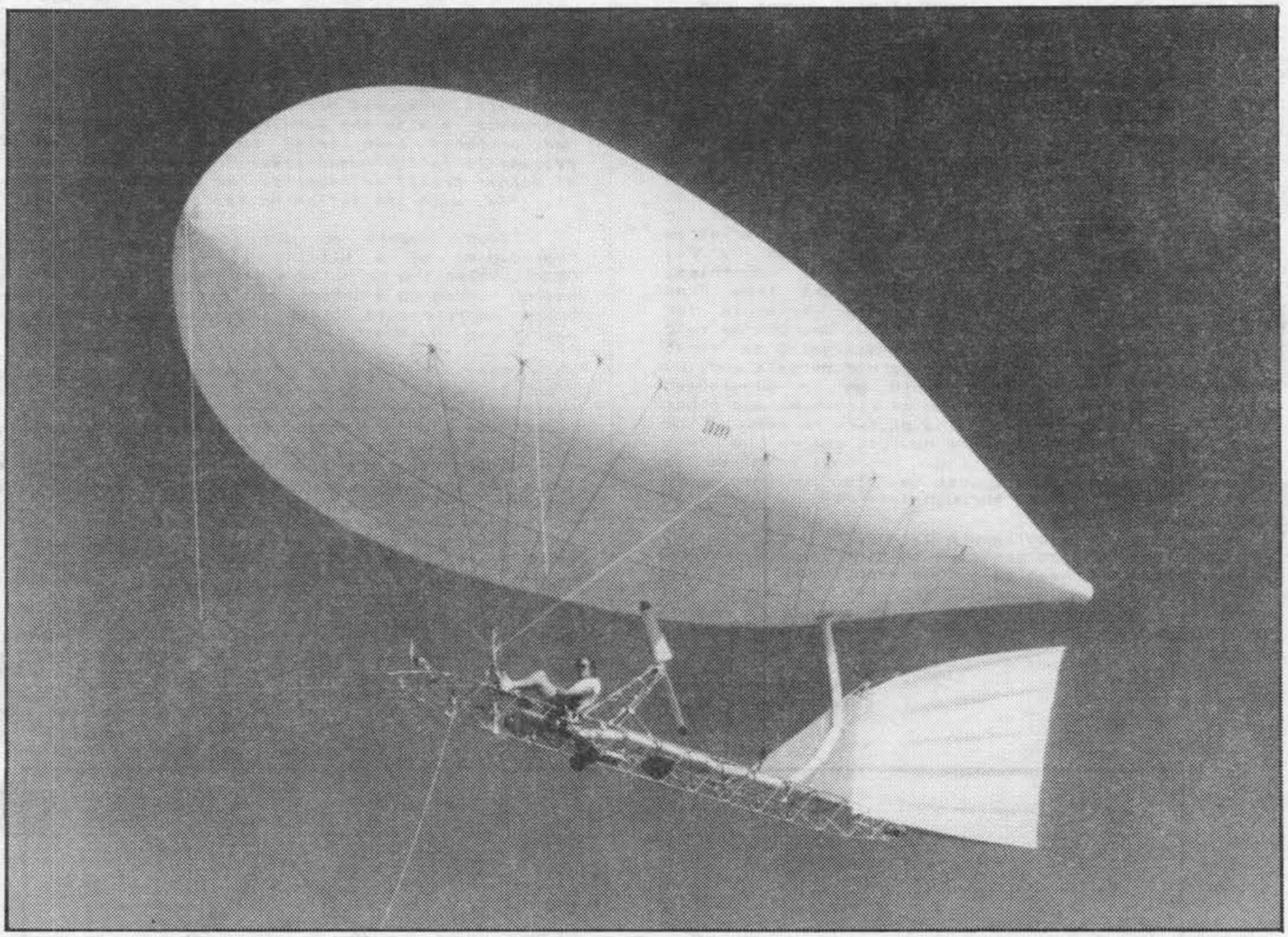

Photo by Bryan Allen, Wizard of Odd, Inc.

The HPAirship *White Dwarf*

Piloted by its designer, Bill Watson, the White Dwarf *pedal-powered airship, conceived and owned by the popular comedian* **Gallagher**, *is filled with aproximately 6000 cubic feet (170 cu. m.) of helium. The 5-1/2-foot (1.6-m)-diameter propeller, mounted on a pylon behind the pilot, can have its thrust angle altered through nearly 100 degrees to allow altitude control via a lever seen in the pilot's left hand. (Thrust vector shown is approximately 25 degrees forward of vertical.) The large rear-mounted rudder, here turning the craft to the left, is controlled by a handle to the pilot's right. Two triangular tanks, under and behind the pilot, carry water ballast. The number on the envelope, 10AYY, is an ultra-light-aircraft registration number - no licensing is required to fly the* White Dwarf.

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WIDENING HORIZONS FOR HUMAN POWER

The last issue of *Human Power* was almost entirely devoted to boats, and the exciting achievements of Alec Brooks and Allen Abbott with their *Flying Fish* hydrofoil, since pedalled by Steve Hegg to an unofficial - as yet - record, seem to be stimulating competitive activity around the world. In this issue, John Langford tells the story of the design and development of the HPA *Monarch*, and the capture of the third Kremer speed prize. By now at least the second and third prizes have been claimed (that is, HP aircraft have been flown at more than five-percent faster than the previous record in each case) and I hope we can have reports from the teams involved in the next issue of HP.

But the mind-altering contribution to this issue will be Bryan Allen's argument for non-Kremer lighter-than-air vehicles, and his description of the HP blimp, *White Dwarf*. He makes a strong case for the probability of blimps becoming popular HP aircraft for clubs.

There is obviously a danger of my being branded as having turned *Human Power* away from land vehicles. It is certainly true that I have solicited articles in other fields to stimulate thinking. And another straw in the wind is the article in this issue by Ray Wijewardene on human power in developing countries. In the next issue I hope to have a report from Fred Willkie on his development of a winter tricycle for use in Canada's icy conditions. Fred, who put me into the HPV business by building and redesigning my first recumbents in around 1972, has learned Bengali and, by the time you read this, should be in Bangladesh working on improving the design of rickshaws and other human-powered conveyances. The picture he drew of the need for improvement in these devices before he left was little short of horrifying. He has promised to send us an interim report that may also unleash some of our humanity power through efforts to help in various ways.

But we also need to keep a balance of topics in HP. I have turned away no articles on high-speed land HPVs because none have been sent. We need some! If you need help getting started, ask me for a set of guidelines on writing for HP before you start. Restore your editor's reputation, if any, for lack of bias.

David Gordon Wilson
Editor, *Human Power*

EXPERIMENTS WITH

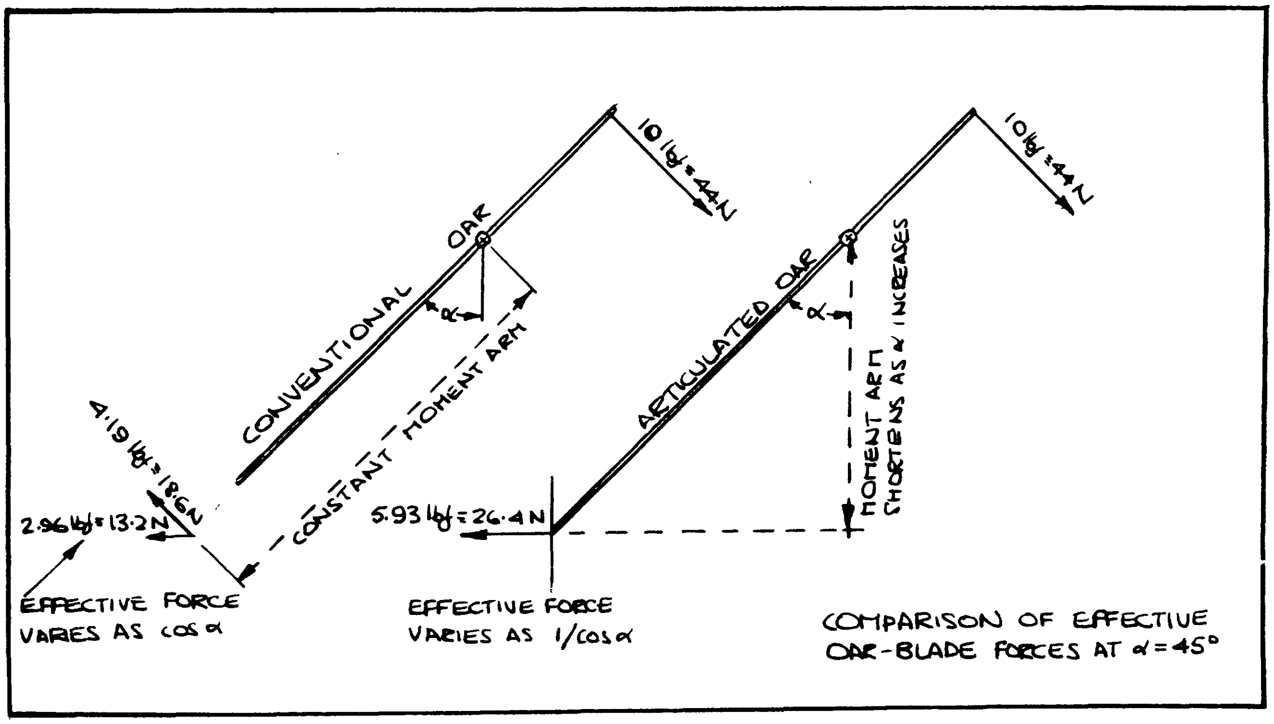
by Otto E. Wolff

Editorial note: Otto Wolff, who is retired and divides his time between Massachusetts and Florida, sent me a note about some experiments he has been carrying out on articulated oars that use a parallelogram linkage to keep the oar blades at right angles to the direction of motion. He did not claim to be original, but I thought that I should try to find out if there was some well-established work on this topic that we might be overlooking. When two friends and I were making rowing shells in the late sixties, we discussed making oars of this type, and we also felt that having the seat fixed to the boat and the rigger and stretchers - the frame carrying the oarlocks and the footboards and "toe-straps" - sliding on the boat would decrease hull resistance by reducing hull-speed variations and the pitching that results from the shift in the center of gravity. I wrote to Otto Wolff to accept his note and to ask if I could introduce it with the warning that articulated oars had probably been tried before but, as we find repeatedly in the human-power field, we have no record of either trials or results. He replied on December 19, 1984, with the following fascinating anecdote.

"Your comments on old ideas being reinvented reminded me of a sliding-rigger boat I persuaded Cedric Valentine to build fifty years ago. A patent search turned up a patent, not on the sliding rigger, but on improvements to the sliding rigger. The patent was issued in 1874!"

This story had force for me because I talked about our plans to make sliding-rigger boats with the superb boat-builder (and MIT Ph.D.) Ted Van Dusen. He later built some beautiful sliding-rigger shells, and one was used to win the Olympics. (As we have come to expect, the Olympic Committee will probably ban them, Ted tells me.) It's a good concept, and people have been thinking about it for over a century. Otto Wolff's generosity in writing about his developments, and even his plans for future work, is that experimenters can build on past experience instead of merely repeating history.

Oars work by pushing water backward. Water pushed in any other direction wastes energy. The momentum (mv) of the backward-moving water equals the momentum imparted to the boat. However, the energy (1/2 mv^2) of the moving water is always greater than the energy



COMPARISON OF EFFECTIVE OAR-BLADE FORCES AT α = 45°

OARS AND RIGGERS

passed on to the boat. Increasing the mass (m) of the moved water improves the efficiency. The size and shape of the blade, its path through the water, and the uniformity of water velocity are important.

In the articulated oar I have been experimenting with as a retirement hobby, the blade is pivoted at the outboard end of the loom. The loom does not rotate, and feathering is produced by a slight movement of the oar handle, transmitting a rotation to a shaft running down the center of the loom.

The conventional oar, swinging through arcs of 40 - 50 degrees either side of center, becomes less efficient as the angle departs from the perpendicular. On the other hand, the articulated oar maintains its efficiency and actually produces more thrust at these angles, as is illustrated by the diagrams. At present, the blade area in the experimental oar is about the same as in a conventional oar, but the greater thrust results in greater slippage. A longer blade would reduce the slip and boost the efficiency. Unlike a conventional oar where increased blade length increases speed differentials along the blade, all of the blade of the new oar moves at the same speed, and it enters and leaves the water cleanly and abruptly.

Another potential advantage of the articulated oar is reduced travel of the seat slide, and therefore reduced pitching of the shell. If feathering does not require rotating the whole oar, the oar may take the form shown. The inboard portion of the loom is angled to allow the hands to move farther out at the catch (the point at which the oar blades enter the water). As a result, the initial part of the pull-through, which brings the blade up to boat speed, involves a shorter travel of the slide and with it a reduction in boat check. In addition, the hands are in a more effective position at the finish.

Checking - the deceleration of the boat resulting from the acceleration of the rower - may also be reduced by storing the rower's kinetic energy at the end of the slide and recovering it during acceleration. A possible arrangement using springs is shown. Two springs arranged to center the oar at mid-stroke run free from the washboard to a capstan at the gimbal. These springs may be contrived also to balance the oar. In the interest of lightness and corrosion resistance they may be made of graphite-fiber-reinforced resin.

Otto E Wolff
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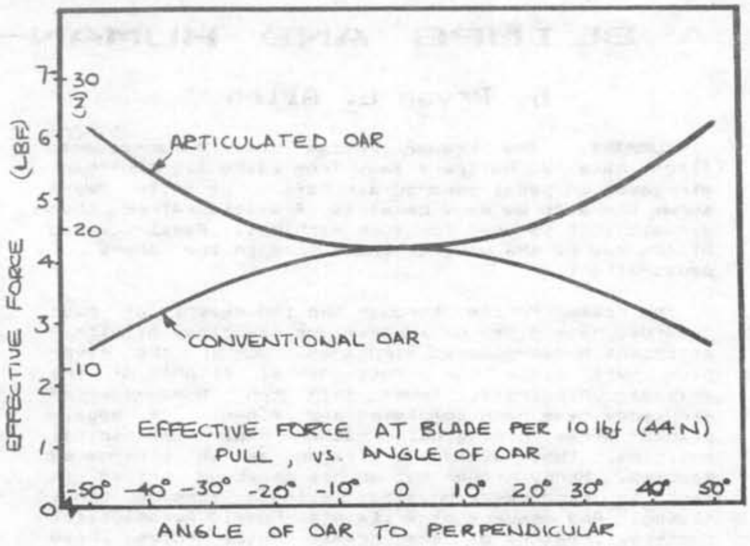
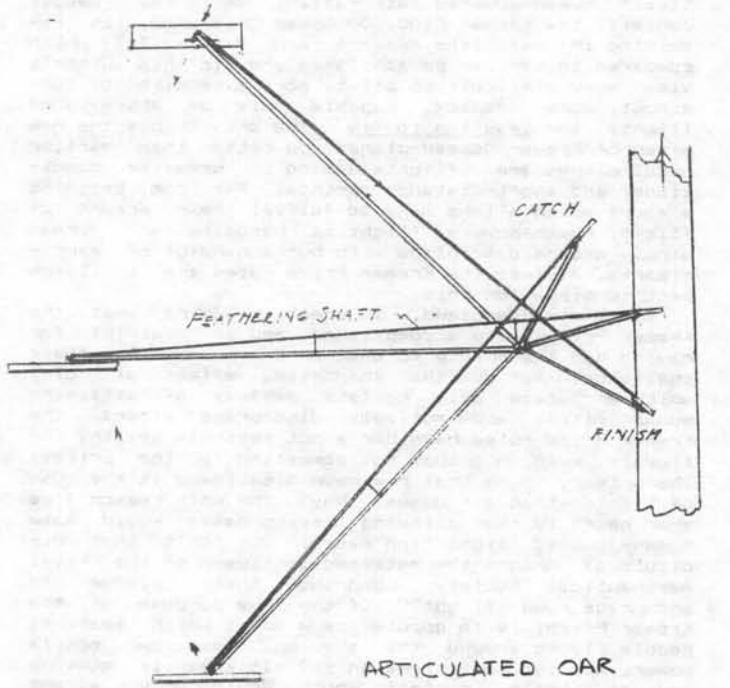
More photos on page 20.

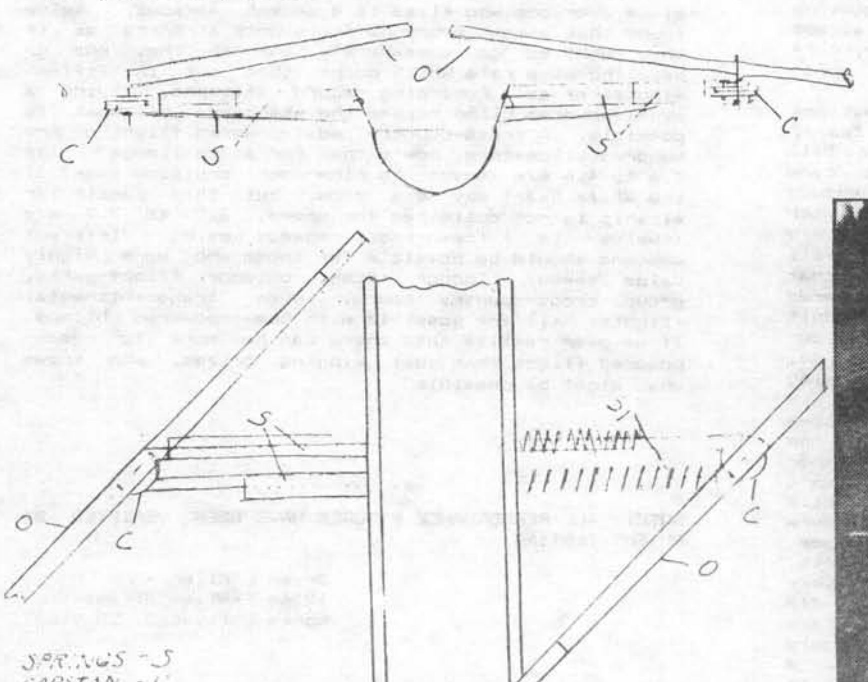




ARTICULATED OAR

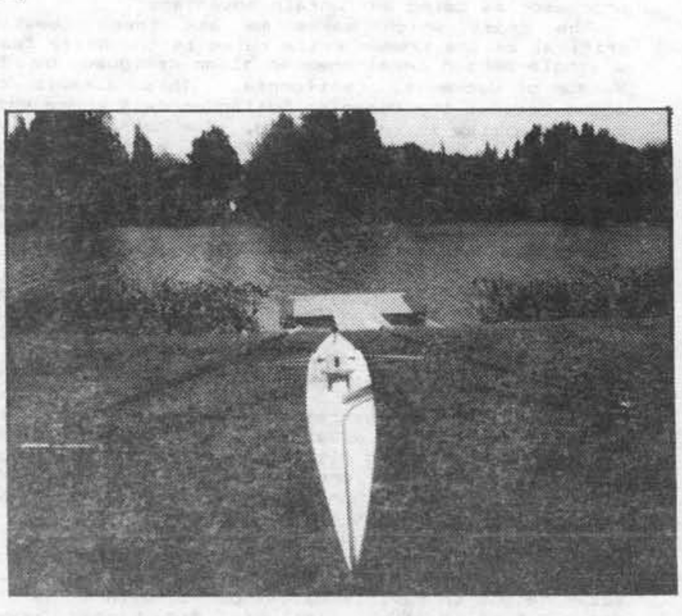
EFFECT OF OFFSET HANDLE

OEW 1-16 35



SPRINGS - S
CAPSTAN - C
OAR - O

ENERGY STORAGE CONCEPT



The articulated oar mounted for trials on a rowing shell.

BLIMPS AND HUMAN-POWERED FLIGHT

by Bryan L. Allen

SUMMARY: The Kremer Prizes for human-powered flight have led builders away from using lighter-than-air gases in pedal-powered aircraft. The *White Dwarf* shows there to be many benefits if static rather than dynamic lift is used for such machines. Pedal-powered blimps may be the wave of the future in the arena of pedal-flight.

The Kremer Prizes, through the inducement of cash rewards, have given us a marvelous new class of ultra-efficient human-powered airplanes. But in the five-plus years since the cross-channel flight of the *Gossamer Albatross*, fewer than ten human-powered airplanes have been completed and flown. If pedal-planes were biological rather than mechanical entities, they would be listed as an endangered species. Henry Kremer put up his generous prizes in part to encourage physical fitness through sport flying. And members of Britain's Royal Aeronautical Society, creators of the Kremer Prize rules, have always maintained they sought to encourage "more practical" human-powered aircraft. Yet the newest contest, the Kremer £100,000 Speed Challenge, is resulting in craft like *Monarch* and *Bionic Bat* which compared to earlier pedal-planes are (in this author's view) more difficult to pilot, more expensive to construct, more complex, capable only of abbreviated flights, and less fun to fly. The only things the new breed of Kremer "speed-planes" do better than earlier pedal-planes are: flights upwind in breezier conditions, and short-distance sprints. Far from becoming a sport which allows many to fulfill their dreams of flight, human-powered flight is becoming an increasingly arcane discipline with but a handful of participants. I feel the Kremer Prize rules are in large part to blame for this.

Don't misunderstand. I greatly admire what the Kremer Prizes have accomplished, and am grateful for having had the chance to take part in meeting their challenge. But by the channeling effect of rules which encourage only certain *methods* of attaining human flight and actively discourage others, the Kremer Prize rules have had a not entirely healthy influence, even on groups not competing for the prizes. The primary thing that has been disallowed is the use of lighter-than-air gases. Why? The only reason I've ever heard is that allowing lifting gases would make human-powered flight "too easy". But isn't that ridiculous? Aren't the esteemed gentlemen of the Royal Aeronautical Society ignoring their pledge to encourage human flight?? If the true purpose of the Kremer Prizes is to popularize a sport which features people flying around the sky on their own muscle power, why put conditions on it? It's as if someone had a literary contest which would only accept handwritten entries presented on home-made paper, forbidding anything written on a typewriter or word-processor as being an "unfair advantage".

The craft which makes me ask these questions critical of the Kremer Prize rules is the *White Dwarf*, a single-person pedal-powered blimp designed by Bill Watson of Van Nuys, California. This airship came about because the comedian Gallagher felt there should be things like it in the world. Our experience with this machine is that it deals much more effectively with the problems of cost, weather limitations, skill demands, pilot fitness, and structural complexity that have so far plagued all flyable human-powered aircraft. We have discovered that nearly any adult who weighs less than 114 kg (250 lb) can fly our pedal-powered blimp and have a lot of fun doing so. With the much simpler structure made possible by using helium instead of wings for lift, the *White Dwarf* is stressed for nearly five *g*'s. This strength allows safe exploration of that third dimension, the vertical, which makes flight different from all other modes of travel. Until I flew this airship, I didn't fully realize how constrained pedal-planes are. While testing the *Gossamer Albatross*, we came up with a term for the temptation to fly high: the Icarus Syndrome. With a plane good for one and one-half *g*'s ultimate, flying anytime more than about one meter high was very foolish. Yet so great was the temptation to truly *fly* as do eagles rather than just skimming the surface like a hovercraft or a cormorant that I would sometimes find myself fifteen meters in the air, a fatal height to fall if catastrophic failure were to occur. Such in-flight failures *did* happen several times with both the *Condor* and *Albatross*, luckily at low altitudes. The *White Dwarf* allows pilots of all fitness levels to safely enjoy what I call the "Stairstep Effect"; this is the feeling you get when ascending in a human-powered aircraft, the feeling as if you were walking up an invisible set of stairs into the air. Flying this blimp is truly like dream-flight; if you want to go over and check out the top of a tree, then rise up and drift meditatively in mid-air, with it you can do so. Yet even for more back-to-earth reasons, *White Dwarf* has major advantages. When the blimp is on the ground, we have found it much less susceptible to winds than any other pedal-powered aircraft I know. Ground-handling the Dwarf in 6.2 to 7.2 m/s (twelve- to fourteen-knot) winds requires only two people. The *Gossamer Albatross* would be destroyed if taken outside in such winds, and even *Bionic Bat* is a handful in similar conditions. This blimp was designed with maximum maneuverability in mind; it has proven during flight testing to be capable of turning inside a twenty-meter circle. If some slight compromises were made regarding fin area (more area yielding less maneuverability), there is no reason why it could not be as outdoor-worthy as the tethered aerostats on which it is based. Raven Industries, which manufactured the envelope for the *White Dwarf*, rates their TIF-6000 Adverblimp design (incorporating stabilizing fins but otherwise identical to our envelope) as capable of withstanding up to 20.6 m/s (forty-knot) winds when properly tethered. Many fixed wing ultralight airplanes on the market will be smashed flat by such winds, so I need not mention what would happen to a pedal-powered airplane caught outdoors in similar conditions.

The cost of helium is certainly a strike against pedal-powered airships. We have found, though, that by careful shopping a load of helium can be obtained for less than $600 in our area. Once filled, the blimp loses about one to two dollars of helium per day, and a fill of helium should last many months before it becomes overly contaminated by air leaking in. These figures show it isn't very thrifty to have a pedal-blimp unless you plan to use it often, and you shouldn't plan on moving it around much (unless you fly it to the destination!) But for a group of human-powered flight enthusiasts who have access to a good flying area, the lower purchase price of a blimp compared to a good pedal-plane makes the airship more economical to own even *including* helium costs. Another indication of its utility is that Gallagher felt the blimp was economical and versatile enough to be able to justify building it as a prop for his performances, something he did *not* feel about pedal-powered airplanes.

Far from making things "too easy", the *White Dwarf* gives everyone who flies it a decent workout. We've found that almost everyone feels once airborne as if they ought to "go somewhere", and so they end up pedaling at a rate which poops them out in fifteen minutes or so. Regarding record attempts, flying a pedal-powered blimp raises the standards of what is possible. A cross-country pedal-powered flight of one hundred kilometers, how's that for a challenge? The 3.6 to 4.6 m/s (seven- to nine-knot) cruising speed of the *White Dwarf* may seem slow, but this particular airship is not optimized for speed. 6.2 to 7.7 m/s (twelve- to fifteen-knot) speeds using different designs should be possible for those who more highly value speed. Indoor races, outdoor flight-parks, group cross-country tours, even transcontinental flights: all *are* possible with human-powered blimps. If we ever realize that there can be more to human-powered flight than just winning prizes, who knows what might be possible?

NOTE: ALL PERFORMANCE FIGURES HAVE BEEN VERIFIED BY FLIGHT TESTING

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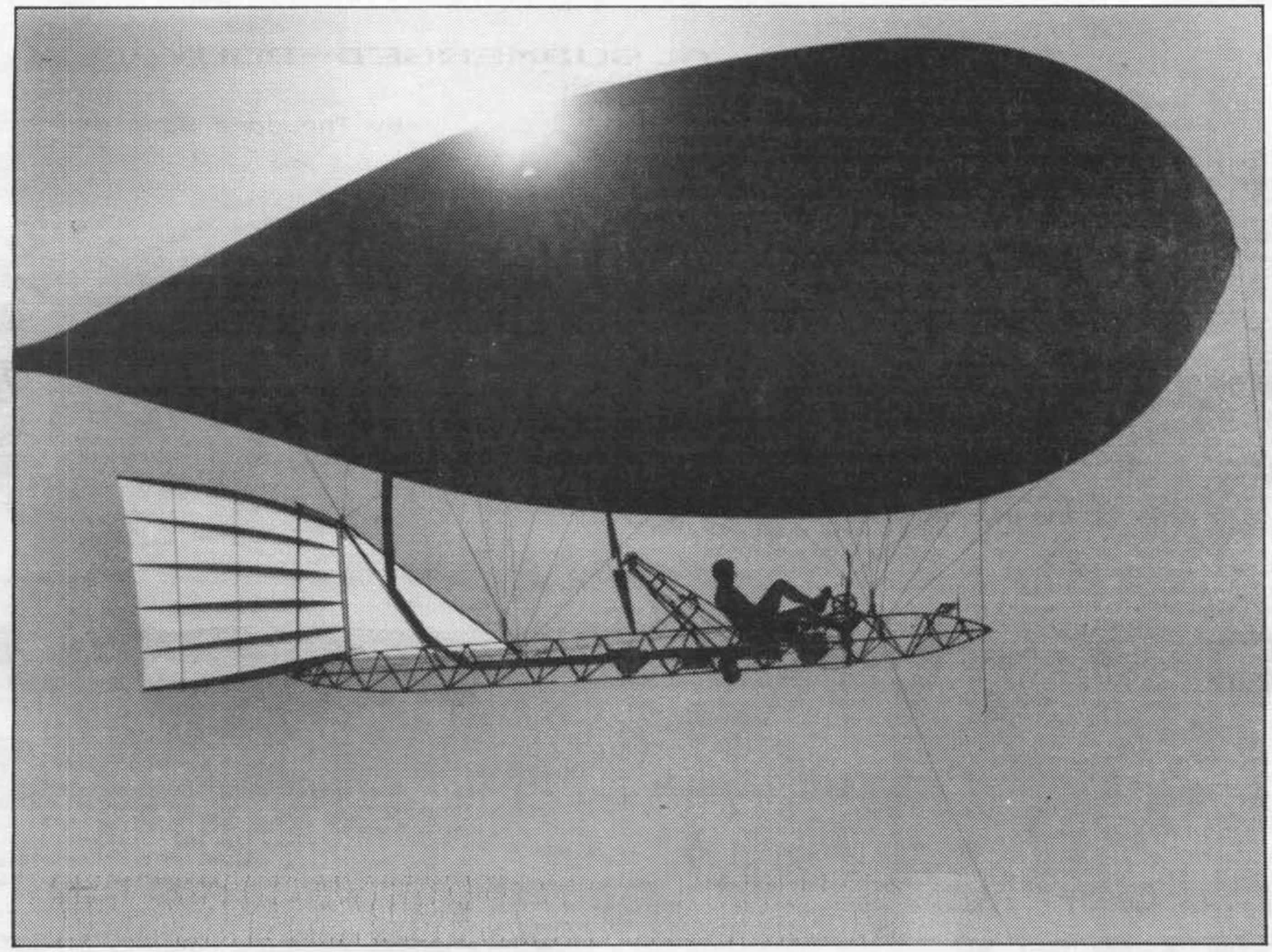

Photo by Bryan Allen, Wizard of Odd, Inc.

The White Dwarf, conceived and owned by comedian Gallagher, flies against an early-morning sun near Camarillo, CA, piloted by its designer, Bill Watson.

Specifications of WHITE DWARF:

Powerplant - Human power via pedals
Length - 14.6 meters
Height - 8.2 meters
Width - 4.6 meters
Envelope volume - 176 cubic meters
Lifting gas - Helium
Seats - One
Empty mass (no ballast) - 66 kg
Gross mass - 180 kg
Pilot mass range (sea level) - 40 to 114 kg
Pilot mass range (5000 feet) - 40 to 96 kg
Minimum speed - Zero m/s
Cruise speed - 4.2 m/s
Maximum speed - 6.2 m/s
Range - Depends on physical strength and endurance of pilot
Envelope type - Raven Industries TIF-6000, modified
Fuselage materials - Aluminum tubes, mainly 2024-T3, with aluminum gussets and stainless bracing cables.
Propeller - 1.63 m diameter with ground-adjustable pitch, spruce/foam
Altitude control - Lever on left side of seat alters thrust vector through 100 degrees
Lift equilibration - gas valving and water-ballast disposal, controls on left side of seat.
Directional control - Wheel moves rear rudder through 160 degrees total travel
Fuel capacity - Zero gallons

MR PROPELLER

So far, all the human-powered vehicles that have broken records or won awards in the air or on the water have been propelled by - propellers. That is not remarkable. What is noteworthy is that every propeller, whether on aircraft or on boats, has been designed by methods that come directly from one person: Gene Larrabee, who retired recently from the faculty of the Aeronautics and Astronautics department at MIT.

His design had a dramatic debut. It was being used on a delightful but noncompetitive HPA at MIT, the *Chrysalis*. Paul MacCready heard that the MIT aero students had a slow biplane with a great prop, and asked if he could use the prop for his *Gossamer Albatross* in its attempt on the Kremer cross-Channel prize. Rather than being grounded without a prop, the MIT group (in the person of Mark Drela) designed a specific propeller for its AeroVironment rivals. Paul MacCready had it made and fitted to the Albatross. The first time Bryan Allen took the plane up with the new propeller, he stayed aloft for an hour, instead of the ten minutes to which fatigue had previously limited him. The higher efficiency of Larrabee's design approach was convincingly demonstrated. From then on, everyone had to use a so-called "minimum-induced-loss" design.

Gene Larrabee will modestly point out, as he did in his article in the last HP, that his methods are simply developments of those previously laid out by Betz, Prandtl, and Goldstein. So be it: all good ideas seem obvious once they have been proven. Gene Larrabee was nevertheless the person who enabled some significant achievements to take place when they did. If he lived in Britain he would stand a good chance of being knighted "Sir Propeller". Here he will have to make do with being Human Power's "Mr. Propeller". Thank you, Gene.

Dave Wilson
15 Kennedy Road
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A SUBMERGED—BOUYANCY

by Theodore Schmidt

This fascinating review is about one-half of a paper in a symposium at the Royal Institution of Naval Architects, London, held on November 9, 1984, called "HUMAN-POWERED MARINE VEHICLES: OARS PROPELLERS, PADDLES". The complete set of the proceedings of the symposium can be obtained from the RINA, 10 Upper Belgrave Street, London SW1X 8BQ, UK, for $15.00.

This paper is mostly about maximum possible speeds of some types of HPBs and the construction of one type of radical design.

RESISTANCE TO MOTION

The weight of the boat and rider can be supported by surface or submerged bouyancy, by planing surfaces or foils, or by combinations of all these. Each method has different amounts of skin friction, pressure drag, wave drag, induced drag and others, all of which scale up differently with increasing speed.

At low speeds, surface-bouyancy hulls have very high lift-to-drag (L/D) ratios and extremely efficient craft are possible without much sophistication, even using human power. A person can pull a barge weighing many tons at walking speed or propel himself slowly with a quite simple craft, using less effort than walking.

At higher speeds, all drag sources increase, but especially wave drag, which effectively limits the speeds of most surface shapes other than very long, thin ones. Modern racing shells are highly refined craft with hulls of this type optimized for mimimum combined wave drag and skin friction.

Wave drag can be eliminated by using deeply submerged bouyancy hulls, which are then limited only by skin friction and some pressure drag.

At even higher speeds, skin friction becomes so large that less drag is incurred by supporting the boat on small hydrofoils or ultimately ground-effect airfoils. A separate class of vehicles has moving-skin mechanisms to reduce skin friction.

SUBMERGED-BOUYANCY HULLS

The drag on fully submerged streamlined "torpedo" shapes is predominantly skin friction with some pressure drag caused by the boundary layer separating before reaching the tail. There is also some wave drag, depending on the depth of submersion, becoming negligible when the shape is submerged more than five diameters. The skin-friction drag coefficient (C) which is based on the wetted surface area of the shape, is a function of the Reynolds number (Re) and for slim streamline shapes is very near the Blasius and Schoenherr lines for laminar and turbulent flow, respectively. As seen in the graph, there is a region of transition, where the value of $C_{D_{WS}}$ can lie anhywhere between the two lines, depending on how far along the shape the boundary layer gets before turning turbulent.

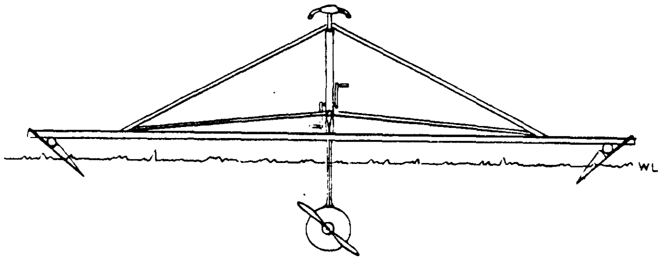
A 3-meter-long shape going 5 m/s (10 knots) has a Reynolds number of about 2×10^7 in ordinary water. It would seem from wind-tunnel and tank tests that there is no hope of laminar flow in this region, but if the flow can be kept laminar by the use of certain tricks, $C_{D_{WS}}$ would be very low indeed.

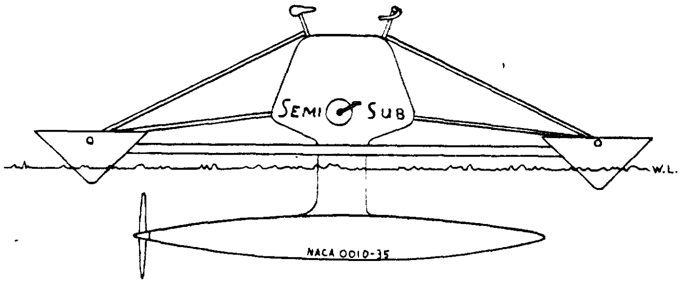
Slender shapes have less pressure drag than thicker ones, but have more wetted area for the same volume; the optimum length-to-diameter ratio is given in (2) as about 4:1 for deeply submerged shapes, but this isn't very critical.

LAMINAR FLOW

In order to keep the boundary layer laminar as long as possible, sections are used that have their greatest thickness (and hence point of minimum pressure) quite far back from the nose, sometimes as much as 65%. Carmichael, Kramer, and Knoll have used shapes with such sections for gravity-powered underwater vehicles and report laminar flow up to Re = 1.8×10^7 and very low values of $C_{D_{WS}}$. This was probably possible because the tests were conducted in still water with no machinery vibrations to facilitate boundary-layer transition. Further methods to keep extensive laminar flow are the following.

The boundary layer can be sucked away by making parts of the hull porous and pumping out the water (4). This also removes pressure drag, as there is then no separation and no wake. If the suction is done correctly, drag coefficients can be halved (2).





Long-chained molecules such as polyethelene oxide can be pumped out ahead of the hull or leached out through the skin. This damps out the vibrations and eddies which are the initial cause of boundary-layer transition. These chemicals can be of very low toxicity and are cheap enough for use in a speed-record attempt.

If any propeller is used positioned at the stern, it will accelerate water flowing toward it and thus counteract the effect of skin friction slowing down the boundary layer, which is what causes separation in the first place. A special boundary-layer propeller was also used by Carmichael *et al* in one of their vehicles (3).

The hull can be covered by an elastic or spongy skin, imitating that of the dolphins, who are very fast swimmers and probably achieve complete laminar flow with their special skins and muscular control over the body surface.

A certain degree of adjustment of Re is possible by choosing the water for a record attempt. The kinematic viscosity of water (contained in Re) is about twice as high (and thus half the Re value) for nearly freezing water rather than pleasantly warm water, and it is also about 10% higher for salt rather than fresh water.

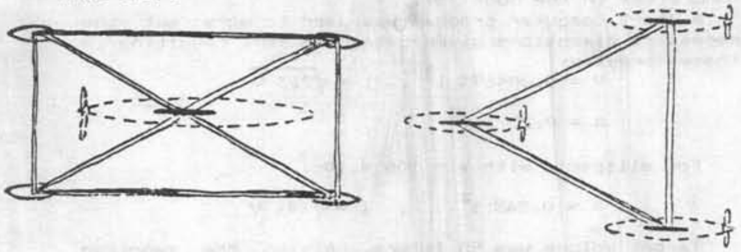
STABILIZATION OF SEMI-SUBMERSIBLES

Submerged bouyancy big enough to contain a person would have at least ten times the drag of the optimum size needed for bouyancy. The rider must therefore be perched above the water on a strut, which can contribute as much drag as the hull itself. This configuration is far less stable than even a high circus unicycle, as water cannot resist a push with zero relative speed, and once the vehicle starts to tip, there is also a vertical capsizing force from the submerged bouyancy. At high speed, the submerged float could be steered with quite small control surfaces, and either produce a righting torque directly or, using a bow rudder, steer the vehicle into a fall like a bicycle, thereby causing a righting force. However, in practice, the rider must mount when the vehicle is stationary, and some static stability is needed.

This can be achieved with floats on riggers; obviously the longer the outriggers, the smaller the floats can be. These must bear some proportion of the boat's displacement at rest, because when one float begins to resist a tipping torque, the opposite one is unloaded by the same amount, causing the submerged bouyancy to surface if not preloaded by at least this amount.

HUMAN-POWERED BOAT

Unlike most boats, pitch stability is completely lacking and must be carefully added as a lateral stability. This can be done with very long lateral floats or with a triscaph or tetrascaph arrangement. Obviously the floats will cause considerable drag, even if replaced with hydrofoils, and should be taken above the water at speed, when dynamic control must take over.



Fully submerged hydrofoil boats are not as difficult to stabilize, as at slow speeds a supporting hull is necessary anyway, and at speed the craft can be steered by moving the foils.

Static-stability problems can be mostly avoided by using three submerged hulls (or hydrofoils). They must still be carefully trimmed out at rest and steered in 3 axes at speed, but outrigger floats for mounting are not necessary. With one person on each hull, the complete vehicles would have the same top speed as a single one with no outriggers.

SCALE EFFECTS

Displacement hulls scale up favorably, as wetted surface increases with the power of only 2/3 of the displacement and C will decrease with speed after the rise due to boundary-layer transition. Human-powered ships could therefore be faster than HPBs, although an upper limit would eventually be set by the increased weight of ship's structure necessary per person.

Theo. Schmidt in his inflatable catamaran.

David Owers' canoe HPB is powered by Theo Schmidt at the Thamesmead Festival, 1984.

Hydrofoil boats do not scale up favorably, even powered ones, as the L/D of the foils does not increase, but may decrease due to cavitation.

MOVING-SKIN VEHICLES

Displacement and hydrofoil boats are unlikely to ever exceed about 10 m/s (20 knots). Ground-effect devices could do better, but this would be just as much an air or land vehicle as a boat.

A further class of vehicles does not appear to be intrinsically limited to these speeds. Skin friction can be eliminated almost completely by moving the hull skin at water speed. The friction of good mechanical or magnetic bearings can be extremely low, so if the skin can be adequately supported and recirculated, the overall L/D could be many times that of other systems at speed. As the amount of wetted surface does not then matter much, the hull can be extremely long and thin or wide and flat, thus nearly eliminating wave and pressure drag.

In practice, this is a daunting task. Unless it somehow floats on air or magnetic bearing, the skin must be supported by rollers and will sag between them, creating drag. If the skin is stiff enough to resist sagging, it is likely to suffer considerable hysteresis losses in bending it around. The mechanisms must be superlative to give any benefit.

PROPULSION

All vehicles propel themselves by imparting momentum to some medium, this being water for most boats.

The Rankine/Froude momentum theory of propulsion gives as the ideal limiting (Froude) efficiency of any propulsor:

$$\eta_F = \frac{1}{1 + v/V}$$

where V is the fluid speed at the ideal propulsor, and v the speed increase behind it. (The total speed increase between some distance upstream and downstream is taken to be 2v).

In the case of propellers, this can be written as:

$$\eta_F = \frac{2}{1+\sqrt{1 + C_T}} \qquad C_T = \frac{F}{\frac{1}{2}\rho A V^2}$$

C_T is the thrust coefficient where F is the thrust, ρ the density, and A the swept area of the propeller.

It is seen that in order to obtain a high Froude efficiency, a relatively large mass of water must be accelerated by only a small amount, i.e. for a given thrust, the larger propeller is the more efficient. Fast vehicles can have reasonable effectiveness with small, highly loaded propellers, or even jets or airscrews, but slow boats need relatively large propellers to perform efficiently.

Propellers have other losses than the ones implied by the above; energy is lost in the tip vortices of the blades and in the rotation of the wake. The latter can be counteracted by the use of counterrotating, coaxial propellers and tip losses can be reduced by using high-aspect-ratio blades, but there is a structural limit to this.

Betz and Goldstein worked out a theory for radial distribution of thrust along the blade which gives minimum possible induced drag. This has been refined by Larrabee at MIT and used to design propellers for human-powered airplanes and more recently HPBs. These propellers can just exceed 90% total maximum efficiency; in contrast, motor-boat propellers might have only 50 to 70%. This is because these are often too small, have highly loaded blades which must then be of a small aspect ratio for structural reasons, and often cavitate.

There are many other propulsors utilizing lifting surfaces, but these are usually quite complex. Nature has provided marine creatures with highly efficient and practical bodies and tails for propulsion, but these are very difficult to imitate successfully.

Thrust can also be obtained by using surfaces providing pure drag, such as oars and paddle wheels. It is not very difficult to work out the total efficiency of drag devices:

SUBMERGED-BOUYANCY HUMAN-POWERED BOAT

Consider a hull with drag coefficient of C_{D_H} and related area A_H travelling at speed V and pulling with force F against a drag device with C_{D_D} and A_D which is slipping in the water with speed v. Then power used for propulsion is FV while power input is F(V+v).

$$\eta_{\text{efficiency}} = \frac{FV}{F(V+v)} = \frac{1}{1+v/V},$$

a similar expression as for the Froude efficiency, but here it is the total one. As $V^2 = F/(\frac{1}{2}\rho A_H C_{D_H})$ and $v^2 = F/(\frac{1}{2}\rho A_D C_{D_D})$,

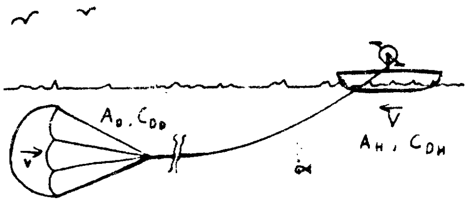
$$\Rightarrow \boxed{\eta_D = \frac{1}{1+\sqrt{\dfrac{A_H C_{D_H}}{A_D C_{D_D}}}}}$$

Comparing the efficiencies of propellers (total efficiencies of minimum-loss propellers are perhaps 5 to 15% less than their Froude efficiencies) with those of drag devices (see table), it is seen that at ordinary sizes, propellers and the like can be far better than drag devices, which are limited by the fact that pure drag coefficients in water do not exceed about 1.5.

At extremely low loadings, a drag device can, however, reach any desired efficiency by making it big enough, whereas propellers of any size are limited by the finite L/D ratios obtainable by foils. The maximum blade efficiency of a pure foil (i.e. assuming no tip and swirl losses) can be shown to be approximately: $\eta_B = 1-2(D/L)$. As foils probably cannot exceed an L/D ratio of 100 in practice, 98% appears to be the limit for propellers. In reality 95% is probably the maximum figure even for very well-designed and constructed ones.

Drag devices must by their very nature operate intermittently, and it is the cost of recycling the rather large surfaces that limits their efficiencies in pratise, even if there appears to be no well-defined theoretical limit.

For example, winching one's boat up to a large parachute deployed in the water could achieve over 99% momentary efficiency, but the energy cost of periodical redeployment makes this method impractical, although it has been suggested by Job (12) for moving icebergs. He has calculated that even with redeployment, total efficiency is higher in this application than using tugboats.



DESIGN AND CONSTRUCTION OF A SEMI-SUBMERSIBLE HPB

First, the section of revolution had to be chosen. A laminar-flow section is preferable. The ideal l/d ratio of about 4 for a deeply submerged hull is too small for a shape operating near the surface, as this would have more wave drag than a thinner hull at the same depth. Therefore the section chosen was the NACA 0010-35, which has a l/d ratio of 10 and is nearly symetrical fore and aft with the maximum diameter exactly in the middle chordwise. This is easier to make than the NACA 66 family of sections with their tricky concave curves, and also appears to have the lowest two-dimensional drag coefficient (at zero lift) in the book (5).

A short computer program was used to work out the necessary dimensions given data from (5), resulting in these formulae:

$$V = 0.004695\, l^3, \quad l = \sqrt[3]{213\, V}$$

$$A = 0.2273\, l^2$$

For ellipsoid with a = 10b = 10c:

$$A = 0.248\, l^2, \quad l = \sqrt[3]{191\, V}$$

Target volume was 95 liters, giving the required length l = 2.72 m and the resulting wetted area A = 1.68 m^2.

The hull was made from Styrofoam discs cut out on a hot-wire jig to the correct diameters and angles, glued together, lightly sanded and filled, covered with a thin layer of glass cloth in epoxy, with some carbon fiber near the central hole for housing the bevel-gear box which connects the propeller shaft to the upper drive system. This is a simple bicycle chain drive, with the chain passing through the strut. Also incorporated in the foam were forward and aft bouyancy trim tanks with control tubes going up the strut. Further tubes were put in for rudder and elevator control, for a pitot speed guage, and for releasing polymers from the nose.

Four stabilizing floats were made in the form of bouyant triangular surface-piercing foils which are connected to the top structure with a framework of metal tubing.

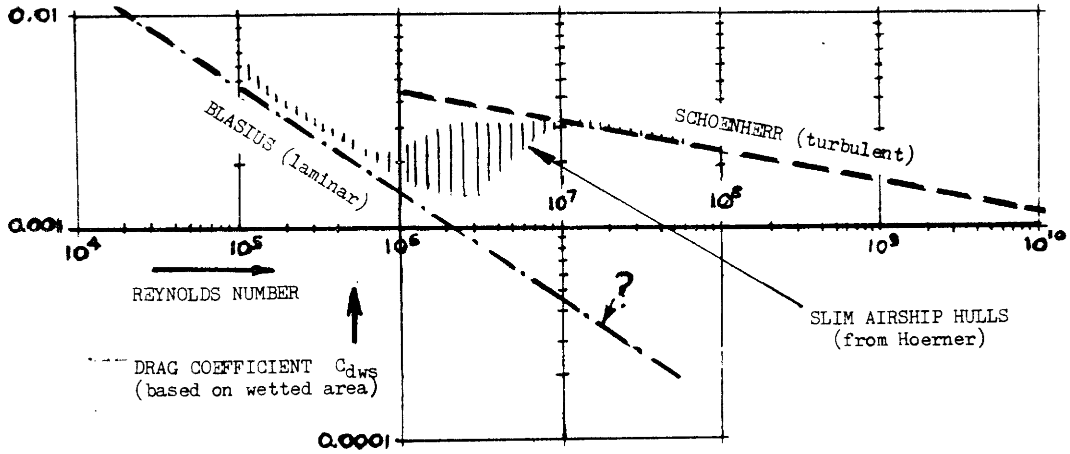
PRELIMINARY RESULTS

Numerous tests in a swimming pool showed the problem of static stability to ba a difficult one, and with hindsight, the chosen bouyancy of 95 kg was too high, even for the 73-kg author, and the trim tanks always had to be completely flooded.

Two outings in the sea revealed that the test boat suffered from insufficient stiffness of the outrigger structure, and the and the ensuing balancing act detracted from pedalling power. This wasn't great anyway, as a calculation error resulted in a wrongly pitched propeller, and the vehicle didn't manage over 4 knots.

HISTORY OF THE SEMI-SUBMERSIBLE IDEA

This is not a new concept; it was proposed by Morwood in 1961, examined by Brewster (11) in 1979, and suggested to me by Sanderson. Huppes also built a similar vehicle in Amsterdam some years ago.



SUBMERGED-BOUYANCY

TABLE: Various max. propulsive efficiencies, all calculated for a boat having drag area $C_{D_H} \times A_H = 0.01$ m^2, travelling at 3 m/s.
Thrust F = 45 N; Power P = 135 N

Froude efficiency of propellers, with diameters:

100 mm	80 %
200 mm	93 %
300 mm	96.5%
400 mm	98 %
500 mm	98.5%

Total efficiency of hypothetical propulsor with ideal blades of L/D = 50, no tip or swirl losses:

500 mm	94.5%

Total predicted efficiency of typical Larrabee propeller:

500 mm	88 %

Total momentary efficiencies of drag devices with C_{D_D} = 1 at optimum angle:

oars	0.1 m^2	76 %
parachute	20 m^2	98 %

CONCLUSION

This project turned out more difficult than anticipated and needs a lot more work before the boat could beat a rowing shell. Many problems could be avoided by using the submerged bouyancy with a low-bouyancy catamaran and utilizing this as a tandem. This would be stable, increase drive efficiency, and reduce relative windage, and although slower than a pure submerged-bouyancy craft, would be faster than a catamaran by itself.

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GARY HELFRICH: MASTER FRAMEBUILDER

interview by Dave Wilson

The human-power movement has more than its share of interesting people. This is the first of what I hope will be a series of interviews of some of them, in which we will ask about their lives and their views of technology. I met Gary Helfrich last year when some of us set up the IHPVA East-Coast Chapter, and we went together to the New York Bicycle Show at which the IHPVA had a booth. Later he gave a talk on welding and brazing to the chapter. He agreed to give his views in this interview, made on January 12, 1985.

DW: How does a native of Orange, NJ, who went to college to study theater, come to be welding mountain-bike frames for Chris Chance's Fat City Cycles?

GH: Well, I made a bad start in welding in a shop class in high-school. Later I took a sculpture course and quite incidentally learned some welding. Before I finished my theater course I quit college and went to California with a rock-and-roll band - Aerosmith. I was the equipment guy. I used to make the sets and stands, mainly out of plywood. I took around a Heli-Arc kit - used to have the argon cylinders sent ahead for us to pick up - and I did the simple welding. The more complicated stuff we sent out. But I gradually became more adventurous.

DW: So how did that lead to mountain bikes?

GH: Plywood work is real boring. And although a rock-and-roll band may seem glamorous, band people in general are not healthy. I was very fit - I used to help load five tractor-trailers each night - and when we came back to this area I used to run into Chris Chance when I went riding. After being a serious racer at high school and in college, Chris had gone to work at Electric Boat, and helped to make submarines. But then his enthusiasm for bicycles led him to making custom bikes. He did pretty well, but eventually reached a dead-end - said he felt more like a tailor than a designer. He met John Troja, who brought with him one of Tom Ritchie's first mountain bikes, and wanted to see if he could come up with an improved version.

DW: Was Tom Ritchie the inventor of mountain bikes?

GH: Tom was a serious racer, and worked at Palo Alto Bicycles. He was one of a cluster of frame-builders in Marin County. I think that Joe Breeze, a laid-back character who maintains that no one ever invents anything, actually put together the first mountain bike, but Tom's name is the first one associates with it. The BMX people were already making 26-inch alloy-rim 4130 welded-frame single-speed specials, but the mountain-bike concept was perceived as being totally new, and it took off.

DW: To digress - why do you think that the mountain bike has been so successful, while recumbents, another bicycle variation, still seem to be struggling?

GH: Most people are intimidated by the thought of riding a bicycle in traffic. And most purchasers of mountain bikes are not previous bike owners. They like the idea of an outdoor sport with almost total freedom, going along old logging roads or railroad tracks. There is an increasing market in outdoor sports. Mountain bikes are advertised very little outside specialty magazines. They seem to sell themselves, even though they are expensive, in the same price category as recumbents. Our lowest-priced bike is around $750.

DW: So you went right from the rock band to mountain bikes?

GH: Not quite. I taught metals technology for three semesters at the Boston Architechtural Center, 1979-80, and helped Chris in my off hours. I asked students to choose something to make. After some prodding, they all chose to make bikes. We reached new levels of nerd-factor with frame angles and overall design. The students got very enthusiastic.

GARY HELFRICH: MASTER FRAMEBUILDER

DW: Very similar to Shawn Buckley's experience at MIT. His seminars on building aluminum bicycle frames were always over-subscribed - often 50 at a time. Gary Klein was one of his students.

GH: One of my students, Larry Dumont, became a framebuilder for Jim DeSilva at Laughing Alley. He still races the stainless-steel bike he made in my class.

DW: I'd be worried about the fatigue resistance of stainless steel.

GH: Agreed. But he used commercial Reynolds 531 forks.

DW: Other than the forks, I'm scared about fatigue failures near the joints of the top and down tubes with the head tube, especially with small frames when the head tube is very short. Then the twisting torque from pulling on the handlebars to counteract pedal forces seems to produce high local stresses.

GH: Don't agree: I've found just the opposite. It's the frames with a long head tube, and therefore a trapezoidal rather than a triangular frame, that seem to have more failures there.

DW: I hope that we can encourage some analysis. But to get back to your story - did you go full time on frame building then?

GH: No, I hadn't enough experience. I learned most of what I know from Prof. Dick Murphy of Northeastern. Wayne Kirk was leading the HPV project, which developed from an earlier ASME go-cart type of project. The Northeasterners were unfortunately influenced by a group of MIT students led by Bruno Mombrinie, who wanted to make a long cigar with a huge number of pedallers. I became an expert at welding bike wheels into pairs for both groups. Prof. Murphy's grounding led me to studying more about welding for myself, and I persuaded Chris Chance to switch from brazing to welding his frames.

DW: So you really believe that welding is better than brazing for bicycle frames. Why?

GH: Well, those beautifully hand-welded BMX competition bikes took a beating and never came apart. During the time we were making both brazed and welded frames, we had far more trouble with the brazed frames.

DW: But brazing doesn't affect the properties of the steel, while in the heat-affected zone near the weld in welded frames, the properties must change for the worse?

GH: You would think so, but we have now made several-hundred welded-frame bikes, and we have never had a weld failure or a failure of a tube near the weld. At first we had a combination of both - a welded frame with brazed-on reinforcements - but we had cracks near the braze and not near the weld. So now we make the head tube, for instance, machined from a single piece and welded, and have had no troubles.

DW: What tubes do you use?

GH: Aircraft-grade chrome-moly. We find it much better than bicycle tubing. But Tange is making a big effort to produce top-quality bicycle tubing. Tange himself, the president of a large Japanese steel company, appeared right here in our workshop. We have a set of his new tubes to evaluate. He feels that there is a stigma against Japanese tubes, and that the only people who would be willing to experiment would be mountain-bike builders, because they are not bound by tradition. Our tubes are 1-1/4-inch (32mm) diameter, and Tange has given us some 4140 tubes that are 0.015-inch (0.38mm) thick at the center and 0.022-inch (0.56mm) at the ends, with the yield improved to 175 ksi (1.21 GPa). Fatigue strength increased by 50 percent through cold working and quality control. You had convinced me during our trip to New York that we should design to fatigue limit rather than yield point or ultimate.

DW: All your welding is TIG (tungsten inert gas). Tell us something about that.

GH: It's the same as Heli-Arc. It was invented by Linde, and used helium at first, because helium was a by-product of natural-gas production and pretty cheap. Now a cylinder is $100. It doesn't like to stay on the work (as a shield) so you have to use a huge flow. So argon which used to be more expensive is now cheaper (about $40 a cylinder), and you can use about a tenth of the flow. It really sits down on the work. We use helium only for welding aluminum.

DW: Why?

GH: Because aluminum conducts heat away so fast we really have to dump in the power. TIG welding is pretty well a constant-current operation. Argon has a low ionization voltage - 18-20 volts - so the power level is moderate. Helium has an ionization voltage of around 35 volts, so we can get much more heat into the aluminum and get the job done faster.

DW: So for the chrome-moly frames you stick to argon?

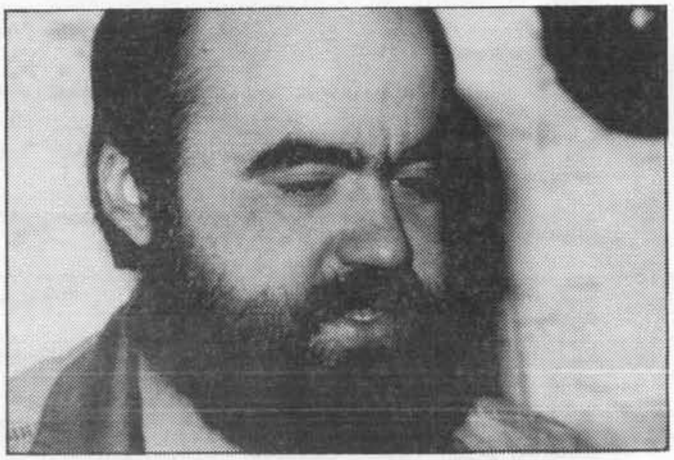
GH: Actually we use a mixture of argon and hydrogen. Wayne Kirk kept hammering away that high-tech people must know more about welding than the bicycle builders. So I talked with people at the GE jet-engine plant at Lynn. They add about 2-percent hydrogen, just enough to wipe off all the oxide layer and turn it into steam. So we have a spotlessly clean surface to work with. More hydrogen and we would have the danger of hydrogen embrittlement.

DW: How do you get that close a mixture? Is that the mixer there?

GH: No, that's the glycol heat exchanger - I use a glycol-cooled torch body. I bought the same equipment that GE uses (indicating an impressive-looking welding device covered with dials and controls, a Miller Synchrowave 300). We buy the pre-mixed argon-hydrogen mixture from Airco.

DW: Are you willing to say what the future holds for materials, designs, and you yourself?

GH: Well, as for materials, I think that we should stay away from aluminum, particularly welded aluminum. Titanium has gotten much less expensive than it was. For a frame set the tubes might cost $65 versus $30 for a steel frame. Pure titanium has superb fatigue and corrosion resistance. I can TIG-weld it and it doesn't need heat treating. I can save a hundred bucks on painting needed for the



GARY HELFRICH: *"...Most people are intimidated by the thought of riding a bicycle in traffic. And most purchasers of mountain bikes are not previous bike owners....*

DEVELOPMENT OF A HUMAN-POWERED RACING HYDROFOIL

by David J. Owers

SUMMARY

A human-powered racing hydrofoil craft has been designed, built, tested and developed over a period of one year. At speeds above 4 m/s (9 mph) the craft requires less thrust than a conventionally hulled boat. An athlete should be able to power such a craft through its take-off speed of about 3.5 m/s (7.8 mph) to speeds approaching 6 m/s (13.5 mph) in foilborne mode. This is approximately the speed of Olympic rowing eights over 2000m.

The first prototype required 287 W of effective power for take-off, which occurred at 3.6 m/s. Due to low transmission efficiency and excess weight, however, the cyclist was able to power the boat to only 3.5 m/s, at which point the hydrofoil supported only 80% of the total craft weight.

It was with this average speed over 200m that the craft won the first European competition for such craft at the Thamesmead Festival of Human Power in July, 1984.

Developments have been made in propeller design which proved successful in tests during September, 1984. These, plus the use of composite materials, will ensure the success of such craft over the coming year. Already a human-powered hydrofoil designed by Alec Brooks and Allan Abbott and powered by Steve Hegg is claimed to have reached 15 mph.

1. INTRODUCTION

Everybody wants to fly. However most of the airborne goals of man have now been achieved: powered flight, human-powered flight, even human-powered airships. Tremendous effort has gone into this sphere of activity and the rewards have been well deserved. Similarly, the development of the humble bicycle, though not so rapid, is now racing ahead. However, progress in human-powered-boat design has been very slow. Racing shells dominate the scene today as they did in 1890.

A human-powered hydrofoil would represent a step-change in technology. There is no *prima-facie* reason why the challenge of hydrofoil "flight" should be any greater than that of airborne flight. Motor-powered hydrofoils have been successful and yet the first attempt to build a human-powered hydrofoil appears to have been M. B. Brewster's (2) in 1979.

This paper should have been a glowing account of how easy it is to build and "fly" such a craft. It remains an account of a "near miss", but is also highly optimistic about future developments. *Thousands* of man-years went into the development of human-powered aircraft before the Kremer cross-Channel prize was won in 1979. About five so far have gone into hydrofoils. This is the account of one of them, together with a theoretical discussion and example of the feasibility of such a craft.

2. THEORETICAL DISCUSSION

The intuitive reaction of most engineers to the suggestion of a human-powered hydrofoil is that insufficient power is available for "take-off". This is not so. The engineers may well prefer to be convinced by the test results given later in this paper. A theoretical analysis does, however, predict the test results with reasonable accuracy, although a caveat must be expressed regarding hydrofoil performance data.

The analysis proceeds upon the following lines.

- We assume that, if the boat will "take-off", then it can continue to travel in foilborne mode, and we judge its operation feasible.
- We assume that it will take off at 3.5 m/s.
- By researching the literature we attempt to predict the drags associated with the following components as accurately as possible:

  i) the hull (in displacement mode);

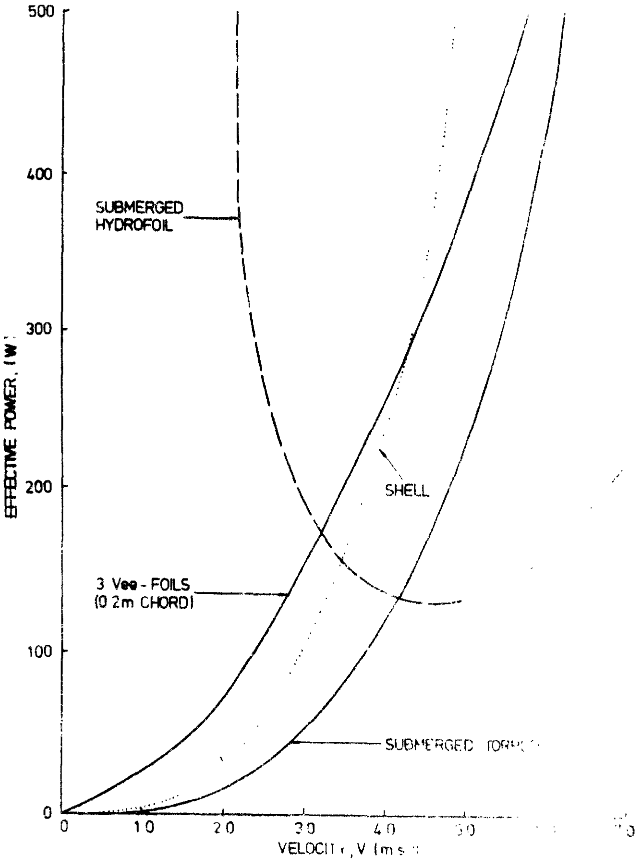


Fig 1 The Effective Power Requirements for

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steel frame. All welded and almost all brazed frames need setting, of course. They all distort during heating. Chris Chance and I cold-set every frame on a granite surface table to within five mils. I think that we may influence makers of racing bikes to go to welding.

As far as design goes, we're making small improvements all the while, such as these stronger and safer dropouts for Phil-Wood-style hubs. We're starting to make a new shape of frame for a trials bike. We think that trials could be the next big sport. It doesn't need speed, but finesse. It's not dangerous And it's great fun.

We don't have plans to grow into a major industry. But Fat City Cycles produced a hundred bikes two years ago, five hundred last year, and we think we could do a thousand this year, from the way it's started. Will I get bored with it? It's possible. But it's not hedonistic like working with a rock band. And I get a great thrill from seeing someone riding something I've helped make. That satisfaction won't go.

As we walked out of Gary's cluttered but effective workshop, talking about the immortality of youth, he indicated a miller set up to miter tubes. Last year he slipped on something while it was on automatic feed. His left hand went through the feed handle, which was rotating, breaking his arm and wrist in several places. The stop switch was just out of reach. Gary is a powerful guy, and he managed to kick the transmission out before his arm was torn off altogether. He said that he has learned that he, too, is not immortal. His arm will always hurt, and have limitations in movement, but it's working pretty well. He grimaced wryly, and said that it was a way of teaching us to have more stop buttons around power equipment.

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ii) hydrofoil profile drag; and

iii) hydrofoil induced drag.

- Parasitic drag is ignored.
- Knowing the speed, we calculate the aggregate power requirement to overcome these drag forces.
- Making assumptions about the various components of the transmission system, we arrive at a human-power requirement.

2.1 Symbols

Throughout the analysis, the following symbols are used.

A_{ws}	Wetted surface area of the hull	m^2
c	Chord of the hydrofoil	m
C_D, C_L	Drag and lift coefficients respectively for the hydrofoil immersed in, and moving relatively to, the water	
s	Span of the hydrofoil	m
V	Relative velocity of the craft passing through the water	m/s
ρ	Density of water	kg/m^3

2.2 Analysis

Hull drag: a summary of literature relevant to this calculation may be found in Owers (3). The formula that emerged as best explaining the the drag of a vee-hulled racing kayak was

$$\text{Hull drag} = 1.27\, A_{ws}V$$

Hydrofoil profile drag: classic aerodynamics defines the drag coefficient by

$$\text{Profile drag} = C_D \rho \frac{V^2}{2}\, sc$$

Hydrofoil induced drag: again from aerodynamic theory:

$$\text{Induced drag} = \frac{2C_L^2 c}{\pi s} \cdot \rho \frac{V^2}{2} sc$$

Hydrofoil wave drag is assumed to be negligible, following the conclusions of Sakic (9) and also Buermann *et al* (10) that it represented less than 1% of the drag of a small craft.

Putting numbers to these drags we need, in effect, to design a boat. We shall use one in which:

$A_{WS} = 0.6$ m

c = 0.102 m

s = 1.524 m

and we shall further assume that the density

ρ = 1000 kg/m

The most difficult numbers to find are the hydrofoil lift and drag coefficients. Many references do not cover the Reynolds-number range 1.0 - 0.6 x 10 encountered by this craft. Of those that do, three are listed in table 1 for a NACA 4412 aerofoil. It will be seen that they are by no means identical. Ramadan's figures (6), obtained from a questionable experiment, give far lower lift-to-drag ratios than the others. However, we will take his results for the purposes of this analysis. Assuming an angle of attack ( ) of 7 ,

we have $C_D = 0.04$

$C_L = 0.76$

Substituting these numbers we obtain:

Hull drag = 61.12 N
Profile drag = 37.98 N
Induced drag = 23.39 N

Total drag 122.57 N

The power requirement is thus:

3.5 x 122.57 = 429 W

2.2.1 Transmission-system Efficiency

Figure 2 shows the transmission system. The efficiencies are as follows.

Drive chain plus derailleur mechanism	96 %
Crankshaft bearings	99 %
Bevel gears and bearings	95.5%
Propeller-shaft bearings	98 %
Propeller	68 %
Overall efficiency	60.5%

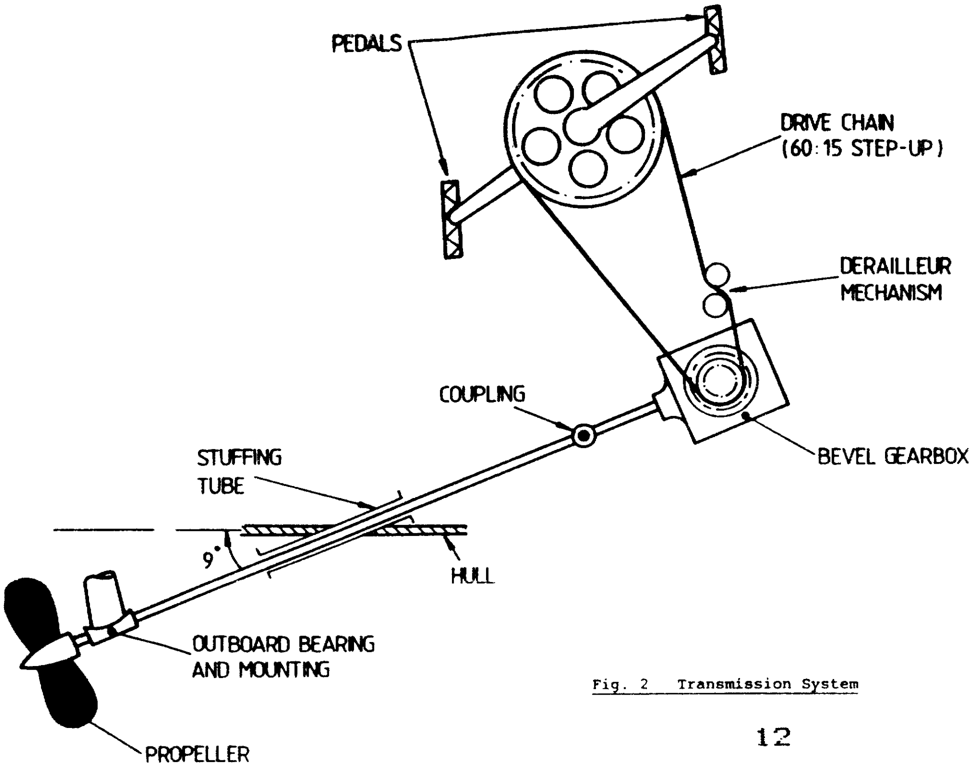

Fig. 2 Transmission System

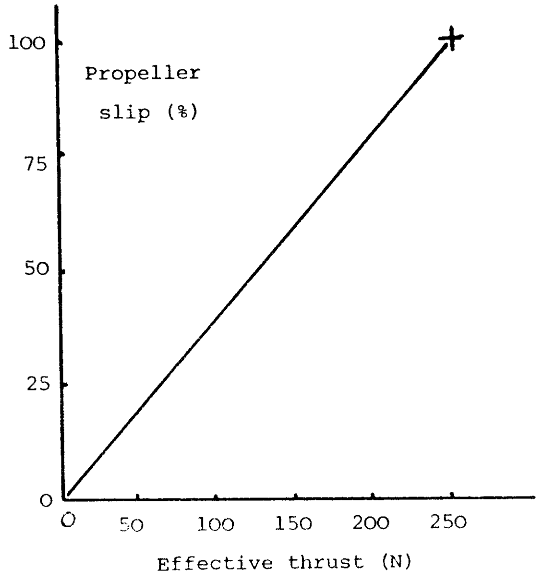

Fig.7 Propeller Slip - vs - Thrust Relationship

Note that the propeller efficiency is the critical factor. This will doubtless be the subject of some discussion.

Using this efficiency, which is by no means optimistic, we obtain a human-power requirement of

$$429 \times \frac{100}{60.5} = 709 \text{ W}$$

Figure 3 shows a good summary of human power capability from Whitt and Wilson's *Bicycling Science* (1982, ref.5). From it we see that an athlete could indeed develop 709 W, but only for twenty or thirty seconds. (It was for this reason that the author did not favor the "jettisoned hull" design proposed in the U.S.!)

One check remains to be carried out on the hydrofoil analysis, and that is to ensure that enough lift is developed by the hydrofoil to support the total weight of the craft. The lift achieved is

$$C_L \rho \frac{v^2}{2} sc = 722 \text{ N}$$

Since it is possible to conceive of a pilot weighing, say, 620 N (10 stone) and a craft weighing 100 N (a Kevlar craft weighs about 30 N), the particular example under analysis supports the feasilibility of a human-powered hydrofoil.

The foregoing example is a very crude simulation of what actually happens. Although it ignores parasitic and wave drag, and postulates a quite impossible *single* hydrofoil, it is in fact a *pessimistic* model, for the following reasons.

In the analysis we assumed that the hull drag at 3.5 m/s would be given by the displacement-mode equation, using the wetted-surface area 0.6 m^2. This is, however, the area *at rest* when the hull supports the entire craft weight of 720 N. By the time 3.5 m/s is reached, the hull is nearly out of the water and the hull drag is dramatically less than the 61 N allowed for in the example.

A desk-top-computer program to try to simulate this effect was written, employing an iterative technique to try to optimize the foil shape for given craft weights and foil-performance data. It was thus possible to test the sensitivity of the power requirement to these factors. The results are shown in figures 4a and 4b.

These predictions have the pessimism of the first example removed and may be truly said to be "idealized". They are useful for comparison, however. Figure 4a shows how a high-aspect-ratio (s/c) hydrofoil will be easier to power to take-off but will make it harder to achieve high speeds. Figure 4b illustrates how the data source affects the predicted power, and why there is really no substitue for building a boat and measuring the drag!

The curve for Ramadan's data (fig. 4b) is the equivalent to the example studied above. We see that take-off is predicted to occur at c. 4 m/s and the power requirement is two-thirds that which we calculated, due to our "double-counting" of hull and hydrofoil drags.

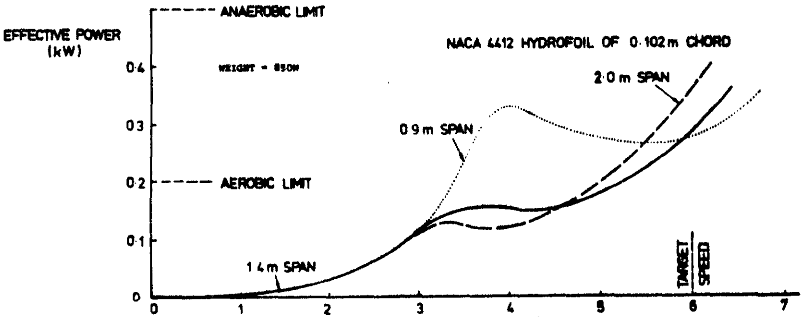

Fig. 4 a) Computer Simulation of Hydrofoil Power Requirement Sensitivity to Aspect Ratio of Hydrofoil

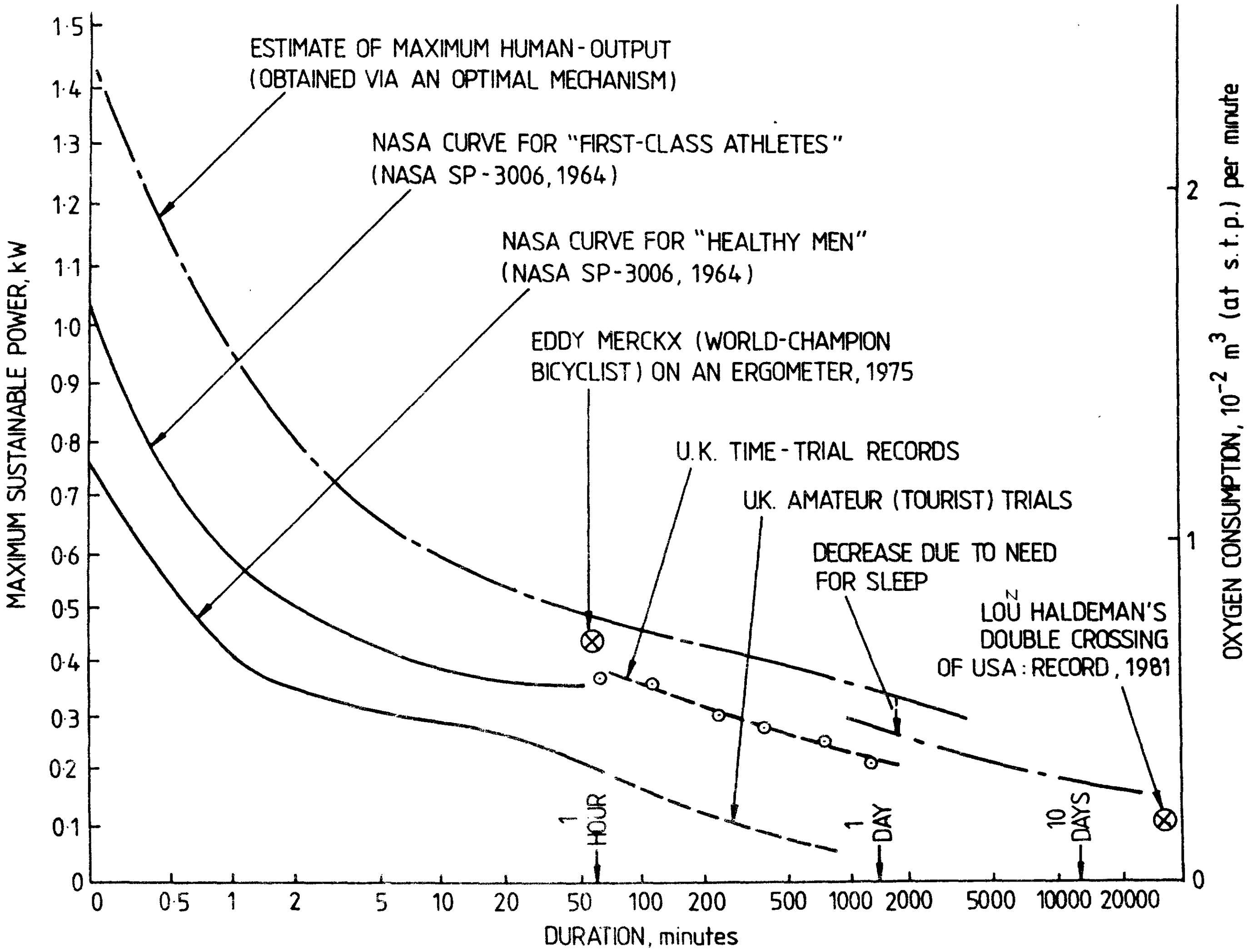

Fig. 3 Summary of Human-Power-Capability Data (Whitt & Wilson (ref. 5))

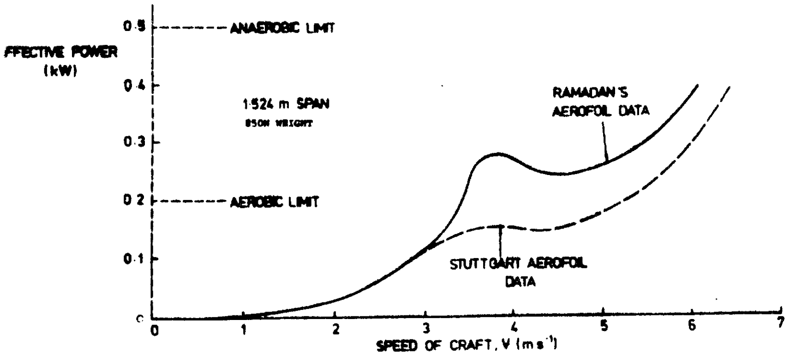

Fig. 4 b) Computer Simulation of Hydrofoil Power-Requirement Sensitivity to Hydrofoil-Performance Data

It is interesting to compare these performances with conventionally-hulled boats. Brewster (2) conveniently did this, although postulating a slightly different design of hydrofoil boat in his 1979 thesis. His results are shown in figure 1. His analysis did not allow for a combined shell/hydrofoil craft, but it can be seen that the critical speed where the hydrofoil becomes superior to a shell is about 3.5 m/s, while it out-performs even a submerged torpedo (*N.B.* Theodore Schmidt article) beyond 4.0 m/s!

I have tried to combine these two sets of predictions in figure 6 to show the whole gamut of predicted power requirements from pessimistic to ideal. We see that at best we are likely to be able to achieve 6.0 m/s with an effective power of *c.* 300 W - well within human capability for extended periods - while at worst we will struggle to take off at this power level, and soon encounter a "wall", making speeds of 5 m/s or above impossible.

It is almost a matter of faith as to which of these analyses you prefer. The author's experiences have "converted" him firmly to the optimistic end of the spectrum. The rest of this paper, on the more practical aspects of this art, aims to preach this gospel.

3. DEVELOPMENT OF A PRACTICAL CRAFT

Encouraged by the foregoing analysis and by James Grogano, who lent me his sailing/sculling hydrofoils, I designed and built a plywood kayak and fitted it with an efficient transmission from pedals to propeller.

The craft was designed for 90% of its weight to be supported by the fully-submerged main foil. The small vee-foil at the bows doubled as a rudder, and it took the remaining 10% load. The main foil was of solid aluminum, but could just be twisted elastically by hand. This proved to be ideal for controlling the roll of the boat - by far the most unstable mode. The pilot was able to control the angle of attack of the foil on both sides. Thus, if the boat rolled to port, he could increase the angle of attack on that side, generating more lift and righting the boat. In eight weeks of tests up to 20 mph the boat never capsized!

3.1 Towing Tests

Shoe-horned into this odd craft at the start of an evening's towing tests, the pilot could have been forgiven for questioning his sanity. The lake is highly exposed, and windsurfers and waterskiers do not *look* as if they are going to make way for you even if you have their peers' permission. Your motor-boat driver is very well-meaning and helpful but may not realize just how precarious this strange boat feels. Your colleague in the motor-boat, whom you pressganged into taking an evening off by offering liquid refreshment at the close, has the speed and tow-rope-force measurements to take as well as making qualitative observations and instructing the motor-boat driver. Will he notice if you fall out? It really doesn't feel very stable...

Musing along these lines, I cheerfully gave the "OK" signal to the motor-boat, and we began to thread our way out to the calmer side of the clay-pit lake. Up til then we had tested the boat *without* foils to validate the hull-drag expression used in the theory. (It was accurate to within 5% up to 6.0 m/s.) The tests so far *with* foils had been disastrous. First the support mechanism had broken, then controll had been such a problem that the whole system had to be re-designed. It was a much firmer and sturdier system that now challenged the waves.

The waves were getting ominously large. from such a low level you need a swell of only a foot or so to obscure everything but Concorde from view. The observer would try to adjust the tow-rope length so that the front foil of the boat did not coincide with a trough in the motor-boat's wake, as this led to "crashes"; the small vee-foil, having no water to support it, crashing back into the foam.

Nevertheless, all seemed as stable as I knew it could be. I signalled for the start of a test-run once we arrived at the calmer, less-populated far side of the lake. As 3 m/s (6.7 mph) was approached, control became trickier. Later we found this was almost entirely due to the towing mode - under human power all is more predictable. Spray from the motor boat, together with the new controls, made an interesting ride. At this point, too, on all previous runs, something had broken and we had had to limp home despondently.

This time, however, we carried on up to 3.5 m/s. All was well, if wet, but then I saw the front foil dip down. This had happened before and meant we were about to "crash". Nothing happened, though. Through the spray I could see my colleague pointing excitedly towards me and shouting at the motor-boat helmsman. Snatching a glance to one side I understood why. The bow foil had not dipped as I had thought - the main foil had *lifted*. The hull was three inches clear of the water!

Then, of course, it did crash.

The boat had taken off at a speed of 3.6 m/s with a tow-rope force of 83 N. Hence an effective power of 300 W was necessary to achieve take-off. Although this is slightly higher than the computer predictions, it is of the same order, and within human-power capability. Once foilborne, the tow-rope force dropped, confirming the "power hump" shape of the predictions (fig. 6).

These results were encouraging, and I went ahead and completed the fitting of the transmission and the propeller in order to test the characteristics of the craft in human-powered operation.

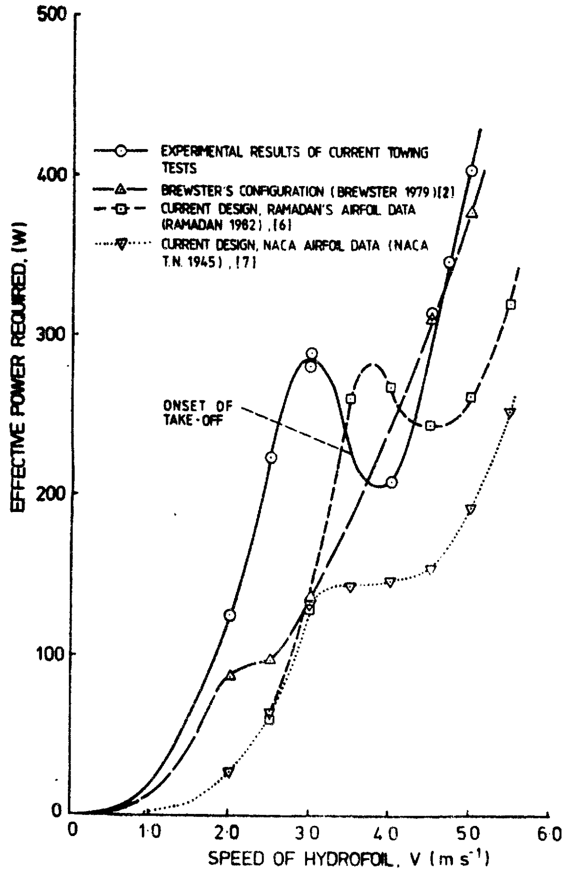

Fig. 6 Synthesis of Past and Current Predictions of Hydrofoil Power Requirements

3.2 Human-powered Operation

Availability of lakes, personnel, and motor boat had severely restricted the possibilities for towing tests. Human-powered trials were less demanding. Two men could handle the whole outing, which could be completed within four hours.

Measurements, however, became more difficult to take. The speed had been measured electronically on the motor boat in towing trials but this arrangement was too cumbersome to consider attaching to the craft itself. We resorted to (distance/time) measurements taken on shore, but accuracy suffered and instantaneous readings became impossible. The thrust, which had been measured by tow-rope tension, now had to be estimated from the propeller slip characteristic, which we assumed was a straight line (fig. 7).

The only points on the curve which we could check were the zero- and 100%-slip conditions. At 100% slip, we measured a maximum thrust of 258 N. This enabled us to calculate the effective thrust from measurement of propeller rpm and speed.

We then optimized the trim of the boat by conducting a series of trials with varying angles of attack of the small bow foil. As expected, an optimum angle emerged (1-1/2°), which gave minimum drag at 3.5 m/s.

We were then able to optimize the crucial operation of the main foil. It was hoped, at this point, that the pilot would be able to power up the boat to, say, 2.5 m/s comfortably with the main foil at minimum-drag angle (~ 1°). Then with a burst of power he should take the craft up to 3.5+ m/s and raise the angle of attack to its maximum-lift condition (c. 7°). The momentum of the boat, plus pilot, would then help him over the "power hump" and into foilborne mode, at which point the foil could be returned to a low-drag angle (~ 4°) while power requirement would be within aerobic capability.

This did not happen.

For two weeks we tried various modifications and methods of "take-off" control. There is no doubt that the ability of the pilot to control the boat confidently and effectively is as important as pure power input. This was found with the *Gossamer Albatross*. However, inexperience at controlling the new boat did not explain the disappointing performance entirely.

The cyclist acting as pilot was fit and strong. We knew from the color of his face that he was putting at least 700 W into the transmission for short intervals. Yet we knew from the towing tests that the effective power from the propeller was less than 300 W (or it would have taken off). Where was all that power going?

3.3 Analysis of Power Shortfall

Plainly the power was being lost in the transmission somewhere and yet I had been quietly congratulating myself on how efficiently and reliably it had all appeared to work. Many People had commented on how well-made the propeller looked.

However, my suspicions lay with the propeller. I lacked the facilities to test its efficiency under comparable conditions, so I had to work "backwards" to calculate it. By confirming the efficiency of the rest of the transmission, I would be able to deduce the propeller efficiency, since I knew approximately the overal efficiency.

To find the transmission efficiency, I simply pulled a pedal with a spring balance, with no load on the propeller. The average force required to start the propeller moving was 15.6 N. This implied a transmission loss, assuming the design pedal rotation of 120 rpm of:

$$\underset{\text{Force}}{15.6} \times \underset{\text{Conversion to radians/sec}}{2\ (120/60)} \times \underset{\text{Pedal radius}}{0.165} = 32.3\ \text{W}$$

Assuming a power input of 750 W this represents a loss of only 4.3% compared with my assumption of 11.1% (para. 2.2.1).

Now this is a very crude method of testing transmission efficiency. It over-estimates the loss because static friction is greater than rolling friction, but under-estimates it due to the absence of thrust forces in the propeller shaft when measurements were taken. However, it is unlikely that the accuracy is worse than 100% and even if this were the case, the design transmission loss is still greater than the measured.

Assuming pessimistically, that the design transmission loss of 11.1% is correct, we therefore obtain an input to the propeller of:

$$750\ \text{W}\ \frac{100 - 11.1}{100} = 667\ \text{W}$$

We know that our output is in the range of 250 - 300 W, since the boat had clearly almost taken off (indeed, the pilot was several times convinced that he had, the boat had risen so much). We assume 275 W, so propeller efficiency becomes:

$$275/667 = 41\%,$$

hopelessly below the design figure (given by the manufacturers) of 68%.

Other factors that reduced the craft's performance can also be singled out. the design weight of craft-plus-pilot was 850 N, but after the strengthening of the main foil-control mechanism, the craft weight had risen to 369 N (83 lb). Even with the strictest diet, I could not have expected my pilot to slim to 500 N (8 stone) and maintain his power output!

The craft was not only too heavy, but too big and, paradoxically, too stable. This was proved by the fact that no one fell out of it.

The NACA 4412 hydrofoils were solid and practical, but a higher-lift section, like the Lisserman profile used on many human-powered aircraft, could enable take-off to take place at lower speeds and hence lower powers.

In short, there are many aspects of the current prototype which can be improved, the outstanding opportunity being to increase propeller efficiency. Already, with the help of Theodore Schmidt, I have made progress in this area.

4. CURRENT WORK

After meeting at the recent Thamesmead Festival in London, Theodore Schmidt (a fellow HPB builder and consulting engineer on kite systems) offered to make a two-blade propeller to my basic requirements (pitch, diameter, and hub design) using ideas promulgated by Gene Larrabee of MIT. In fact, he made two such propellers, both of which were considerably lighter than my aluminum three-blade propeller, and both of his out-performed mine. On a bitter evening on the Thames at Putney we lacked the equipment to make any more than rough estimates of the efficiency improvement, but we think even these first attempts give us 10-20% better efficiencies. Gene Larrabee's computer program "Helice" gives efficiencies as high as 92% for similar propellers and his *Gossamer Albatross* propeller indeed achieved high efficiencies in the high 80s.

The second *Owers Ark* now being constructed has a similar hull and lighter mainframe. Many hydrofoils and propellers will be made for it in order to compare performances of different configurations. Although the design is not yet finalized and I am open to ideas, I am confident that it already incorporates enough improvements to become the first practical human-powered hydrofoil - if I have not already been beaten to it by Allen Abbott and Alec Brooks, and other rivals in the United States.

David Owers
6 Leysfield Road
London W12 9JF
England

David's new boat is being sponsored by BOC Ltd., and is being built at British Aerospace, Heybridge, UK.

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HYDROFOIL

TABLE 1

* Ramadan measured the *total* drag coefficient C .
Since the two-dimensional coefficient C_{D_o} has been used in the calculations shown in this article, the figures have been corrected, in the right-hand column, using the formula:

$$C_D = C_{D_o} + \frac{2\ C\ \ c}{s}$$

where
C_L = lift coefficient
c = chord length (m)
s = span length (m)

Comparison of lift and drag coefficients for the NACA 4412 foil used.

Source	NACA TN 1945		Stuttgart		Ramadan *		Ramadan (corrected)*	
$\alpha°$	C_{Do}	C_L	C_{Do}	C_L	C_D	C_L	C_{Do}	C_L
-2	0.0071	0.20	0.016	0.105	-	-	-	-
-1	0.0070	0.27	0.014	0.255	-	-	-	-
0	0.0070	0.37	0.012	0.350	0.021	0.30	0.017	0.30
1	0.0070	0.45	0.010	0.430	0.022	0.37	0.017	0.37
2	0.0069	0.51	0.009	0.530	0.025	0.43	0.018	0.43
3	0.0068	0.62	0.010	0.620	0.030	0.49	0.020	0.49
4	0.0068	0.70	0.010	0.710	0.037	0.56	0.025	0.56
5	0.0068	0.80	0.011	0.800	0.046	0.63	0.030	0.63
6	0.0071	0.87	0.012	0.800	0.055	0.70	0.036	0.70
7	0.0075	0.95	0.013	0.950	0.064	0.76	0.041	0.76
8	0.0080	0.99	0.020	1.030	-	-	-	-

Another of David Owers' HPB designs is pictured on page 7.

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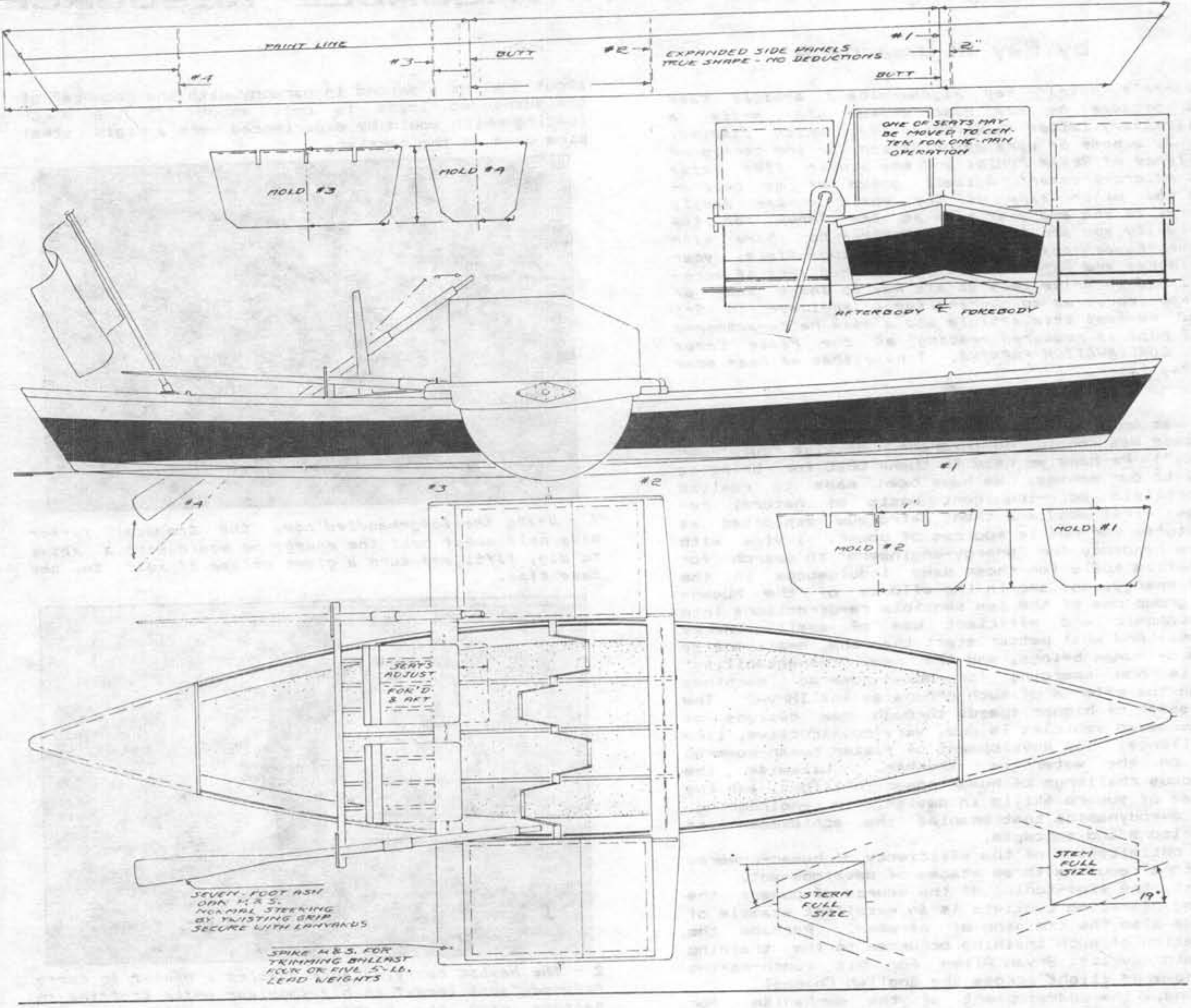

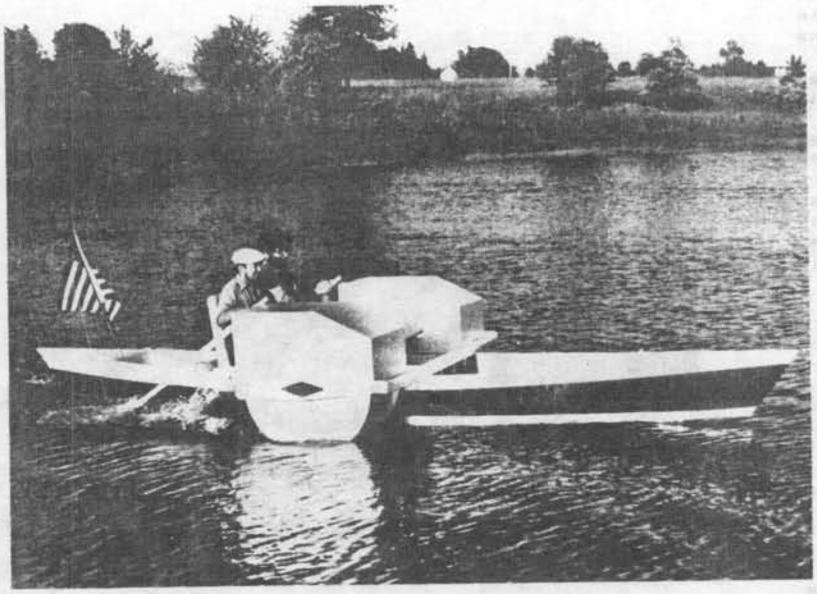

About seven knots at full foot power.

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Paddlin Madeline

In the last issue of *HUMAN POWER*, a discussion of the paddle-HPB *Madeleine* was published without the accompanying illustration, due in part to lack of space, and in part to the poor reproducibility of the drawings supplied. A better copy has been obtained for this volume. Our apologies if the labels are still unreadable - the reader who desires a clear brochure may write to:

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HUMAN POWER: A VALUABLE RESOURCE

by Ray Wijewardene

Editor's Note: Ray Wijewardene's article came about because he was rash enough to write a complimentary letter in November '84, which started: "This is a note of warm appreciation for the continued excellence of HUMAN POWER: and the winter 1984 issue was a record-breaker! A small group of us here - right the other side of the world - are deeply grateful to you and your team at the IHPVA for the opportunity you provide in HUMAN POWER to share with us your "happenings" in this fascinating field, your experiences and experiments." With that sort of accolade I had to write back to ask Ray to share some of his experiences as an agricultural engineer in Sri Lanka. He sent this article and a book he co-authored that I hope is required reading at the Peace Corps called CONSERVATION FARMING. I hope that we hear more from Ray later.

It was only a decade or two ago that anything hand-made was considered inferior - or else "cute" or "crafty"! Perhaps we need to thank OPEC for bringing us all to our senses. We have been made to realize the prolific self-indulgent waste of natural resources: first wood and then petroleum exploited as substitutes for muscle sources of power. I view with alarm a tendency for "energy-engineers" to search for alternative fuels for those same indulgences in the use of energy, and see in the efforts of the human-power group one of the few sensible re-directions into the economic and efficient use of small energy sources. And what better start than the small-energy source of human beings, and the new "respectability" that is now emerging for human-powered machines through the efforts of such groups as the IHPVA? The achievement of higher speeds through new designs of human-powered vehicles is one, very constructive, line of challenge. The development of faster human-powered craft on the water is another. Likewise the tremendous challenge of human power in flight, and the exercise of superb skills in design, in engineering, and in aerodynamics that enabled the achievement of new horizons and concepts.

The optimization of the efficiency of human-powered operations requires three stages of developement.

First, the fine-tuning of the source of power: the training of racing cyclists is an excellent example of this, as also the training of oarsmen. Perhaps the culmination of such training occurred in the training of aviator-cyclist Bryan Allen for his epoch-making human-powered flight across the English Channel.

Second, the development of the mechanism for translating that power, that source of energy, into a form where it could efficiently and conservatively be exploited for the objective in mind. The bicycle pedal-and-chain drive still performs as one of the most efficient of such translational mechanisms.

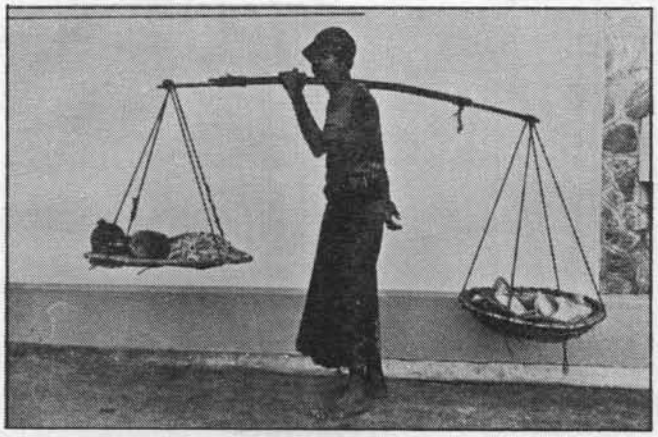
And third, the vehicle which utilizes that translated energy with still further efficiency and economy of the original energy source.

I believe that the achievement of still further excellence in the optimization of human-powered systems will depend on dedicated and individual effort in these three areas of development. I will first describe our own efforts to improve the economy of human power and facilitate its use, starting with two techniques used traditionally in the developing, tropical regions that bear considerable study.

The long-handled hoe in figure 1 has proved in many studies its ability to dig, lift and turn a sod, or even to dig a pit or a drain, with greater economy of energy and time than use of the spade. The hoe efficiently utilizes gravity in the downward swing of the hoe to penetrate deeply. The pull thereafter to raise and invert or lay the sod is much easier than pushing and lifting as with a spade. As any golfer will confirm, the skill that goes into the swing contributes greatly to the impact the club makes on the ball, and this relates to the efficiency with which the golfer harmonises muscle power with gravity to direct the force of momentum optimally.

Figure 2 illustrates the "kadha" or carrying pole (bamboo, usually) as used by hawkers all over the tropics when transporting loads of up to 60 kilograms over level roads. The excellent analysis of the ergometrics of the carrying pole by Oliver F. Campbell of Cornell (1) shows that the shock loading upon the shoulder of a person carrying a 54-kg (120-lb) load with a bamboo carrying pole and trotting along at about 3 steps a second in harmony with the "bounce" of the suspended loads is only about 1/3 the shock loading which would be experienced were a rigid steel pipe used as the carrier.

1 - Using the long-handled hoe, the tropical farmer uses only about half the energy he would with a spade to dig, lift, and turn a given volume of soil in the same time.

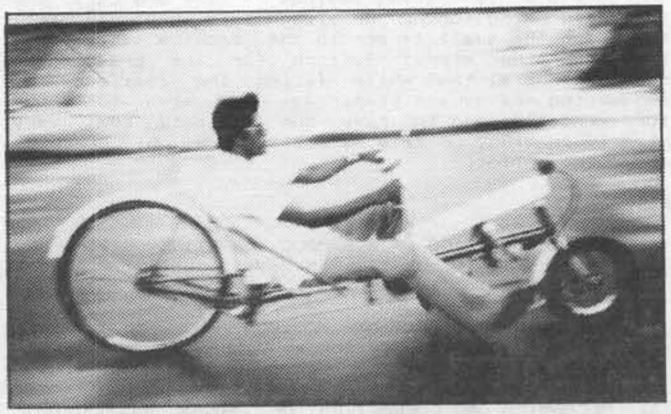


2 - The bamboo carrying pole enables a hawker to carry reduced "peak loads" on his shoulder while trotting in harmony with the bounce of the equally balanced suspensions.

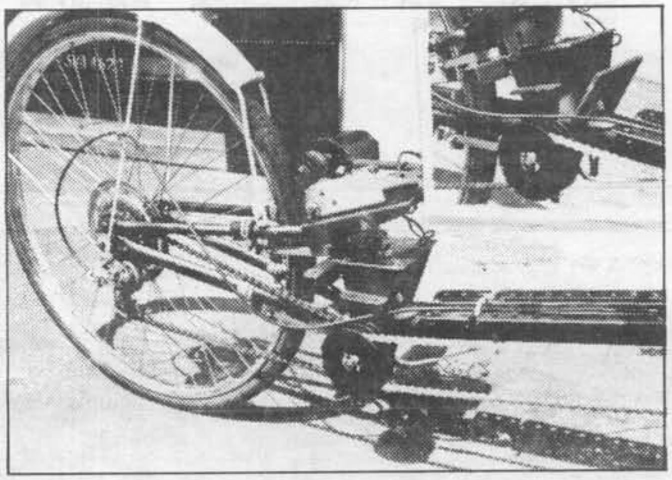
4 - The solar-photo-voltaic panel, batteries, and motor are a non-essential sophistication on this independently-three-wheel suspended recumbent trike for town running. It is convertible in about half an hour into an out-of-town commuter bike, still with independent wheel suspension.

IN THE DEVELOPING COUNTRIES

V. A. Tucker (2) in a paper on *The Energetic Cost of Moving About* analyses how greater efficiency is achieved by birds, fish - and bicyclists - than walking or running in animal locomotion. The book *Mechanics and Energetics of Animal Locomotion* (3) is further fascinating reading for those interested in achieving greater efficiency in the translation of human power into locomotion - whether on land, sea, or in the air. It would appear that springs and similar energy-converting devices will come into much greater use in the future to convert the cyclic retardation of body masses in reciprocal motion for the subsequent acceleration process. As an oarsman it always worried me that the aquatic pedaller using only his legs could propel himself as fast over the water (perhaps faster) as the oarsman using arms, legs, and body! The deceleration at the end of each stroke and energy absorbing coil-up for the next stroke was inadequately re-converted into drive despite the efforts of the oarsman toward rythmic motion. Our efforts (in Sri Lanka) to design a reciprocating pedal drive more efficient than the rotating pedal achieved very smooth and sustained transmission of the thrust of the (reclining) pedaller's legs (figure 3), but did not provide the dramatic improvement we expected. This disappointing result may have been partially because the cyclist was very unused to the reciprocating pedal, but more because we failed to devise a system for cyclic absorption of the deceleration that occurs at the end of a stroke and the conversion of this energy into the subsequent driving stroke. Back to the drawing board! Incidentally, simple measurement of the energy used by the cyclist was achieved through measurement of the carbon dioxide exhaled over a fixed distance. For the present, and until we better achieve harmonic movement of the (reciprocating) masses in a re-cycling of the energies of deceleration, the rotating pedal still reigns!



3 - The "bike-trike" in two-wheeled configuration, here undergoing trials of the reciprocating pedal drive system. Good "drive" but not all that much of an improvement on the standard pedal!



6 - The rear-wheel fork is hinged to the main backbone of the bi-trike, and hard rubber balls inside the wedge-shaped box above the hinge provide excellent "damped" springing. Inset shows the box open. The transfer-sprocket-drive also operates on the same axial pin of the hinge.

7 - Woven cane is used in the shaped reclining seat of the bike-trike to enable the skin of the cyclist to "breathe" better in the hot climate, and thus afford better cooling.

Our studies into facilitating the effort of pedalled transport naturally led us toward recumbents, and we quickly concluded that most of the commercially available designs for recumbent bikes erred in not lowering the cyclist sufficiently to achieve a substantial reduction in both frontal area as well as in coefficient of drag. Lacking a wind tunnel for quantifying our results, we resorted to towing the bikes behind a vehicle at calibrated ground-speeds along the airport runway in various head as well as following winds, the relative airspeed being measured by a pre-calibrated air-speed indicator mounted on the bike. The "pull" of the bike was initially measured by a sensitive (pre-calibrated) "fish-scale" mounted on the rear of the towing vehicle and linked to the

5 - The front-wheel suspension uses rubber shock-cord suspension in a "heel-type" joint. Very necessary on heavily rutted roads in most developing countries.

HUMAN POWER IN THE DEVELOPING COUNTRIES

bike being towed by a 60-m (200-ft) cable. The fish-scale was later replaced by a recording strain-gauge, and correlated with the ground speed and air speed to enable accurate measurement of rolling resistance as well as air resistance at the various speeds. It was interesting that the fiberglass streamlined cowl we built around the bike proved impractical in our tropical (damp humid) environment. Ventilation is essential here, and plenty of it! A further observation was that while the recumbent bike was fine when used for speed runs or for commuting to town, it was not too easy in the continuous stop-and-go of traffic in town, and here the conversion to the trike configuration proved essential for comfort, thus the name "bike-trike". It could then start and stop with the other heavy traffic without wobble.

In the developing world, most of the roads are terrible! Pot-holes and ripples everywhere make standard cycling unpleasant. So we investigated various forms of suspensions, and these are illustrated in photographs 4, 5, and 6. Rubber shock-cords and balls (made locally from our own rubber trees) were the medium of suspension used, and they performed delightfully. In figure 7 you will note the ventilated woven-cane contoured seat we used to help dissipate sweat and body heat quicker. Does the suspension really help? Yes: it not only greatly helps smooth the ride for the rider; it also clearly reduces the energy inputs into propulsion of the vehicle over rutty and potholed roads. This we measured by towing the vehicle at rated speeds over smooth and rutted roads, both with the suspension locked and the suspension operative. Depending on the depth of the potholes, the suspension afforded a reduction in the energy of propulsion of up to 20%. This is substantial! And how? We conclude that the independent wheel suspension greatly reduces the energy lost in vertical acceleration of the bike and cyclist. Seems to make sense!

Where do we go from here? Well, we've learned a lot about improving efficiency in human muscle power. This is particularly vital in our part of the world where muscle power provides 90 to 100 percent of the energy needs for agriculture and also for transport! A soft sack draped over a draught-animal's shoulders, in front of his hump, provided greater comfort than the solid yoke, and increased work output by 20%. While this is not great, it points the direction for future efforts in design (figure 8). We've also learned to think holistically and synergetically. Our studies have emphasized the truth behind the contention (perhaps a "law") that for a given system, the product of energy and duration remains constant. In other words, the impact of "mechanization" has mainly been to impose *higher energy* use with *shorter durations* in place of the *lower energy* use but *longer durations* of manual systems. What we really need, however, is to devise *short-duration, low-energy* systems to achieve the same end objective. For example, in farming, when replacing the bullock in front of the plow with a tractor, did we mechanize agriculture - or did we mechanize the bullock? Had we really studied our objective more deeply, we would have realized that the fundamental purpose of tillage was weed control. We do not need to cut, lift, and turn soil, and precipitate erosion and compact the soil any more, just to control weeds. Alternative methods for control of weeds now use very little energy and achieve great savings in time and cost, and these are being further developed into very practical tools for the small farmer in the tropics (4). But this is another story! Suffice for the present to conclude, here, that while facing the challenge of conserving energy and time, we need also to think fundamentally, and to have our ultimate goal very clearly in mind, or else we shall end by only "mechanizing the bullock"!

8 - A sack draped in front of the draught-animal's hump made it VERY much easier for the bull and greatly reduced fatigue. A considerable improvement on the solid wooden yoke used earlier - and more simple!

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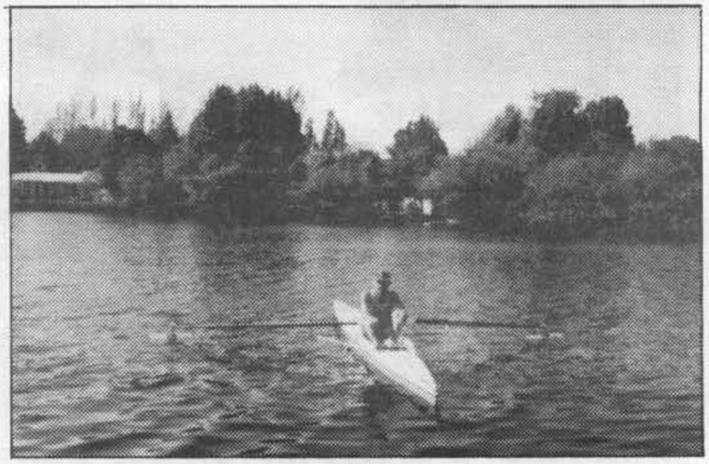


Mr. Holffe rows his articulated-oar equipped shell.

THE MIT *MONARCH B*: First-Prize Winner in the Kremer World Speed Competition

by John Langford and Mark Drela, MIT

Abstract

This paper provides an overview of the *Monarch*, MIT's human-powered aircraft that on May 11, 1984, won first prize in the Kremer World Speed Competition. Designed and built by an all-volunteer team in 88 days during the summer of 1983, the *Monarch* made 29 flights before it was dissassembled and stored for the winter. During the spring of 1984, a revised and improved version known as the *Monarch B* made 35 flights culminating in the record flight. This paper details some of the design considerations and construction details behind the *Monarch*, with particular attention to the aircraft's propulsion system and advanced avionics.

I. Introduction

In May of 1983, Britain's Royal Aeronautical Society (RAeS) announced the third in its series of human-powered aircraft (HPA) competitions. Known as the Kremer World Speed Competition, this new contest offered a £20,000 prize to the first entrant to fly a 1500m closed course in less than 180 seconds (requiring a speed of roughly 20 mph). In a significant departure from the previous Figure-Eight and Cross-Channel prizes, the Speed Prize allowed the use of energy storage. During a ten-minute period before the flight the pilot(s) could store his own energy via whatever means the contestants could devise. The rules also included provisions for official observation, minimum and maximum altitudes, a qualifying flight, and follow-on prizes (£5000 each) each time the record is broken (1).

Upon announcement of the competition, a small group of students at MIT (including the authors, Juan Cruz, and Steve Finberg) began to examine the feasibility of winning the prize. Three other HPAs had previously been built at MIT, including *BURDs I* and *II*, designed to compete for the Figure-Eight Competition, and the *Chrysalis*, flown some 350 times in 1979 as the precursor to a hoped-for entry in the Kremer Cross-Channel Competition. Both of the authors had worked on *Chrysalis*, and much of the technology was transferred from that experience into the newest aircraft, known as the *Monarch*.

II. Design Considerations

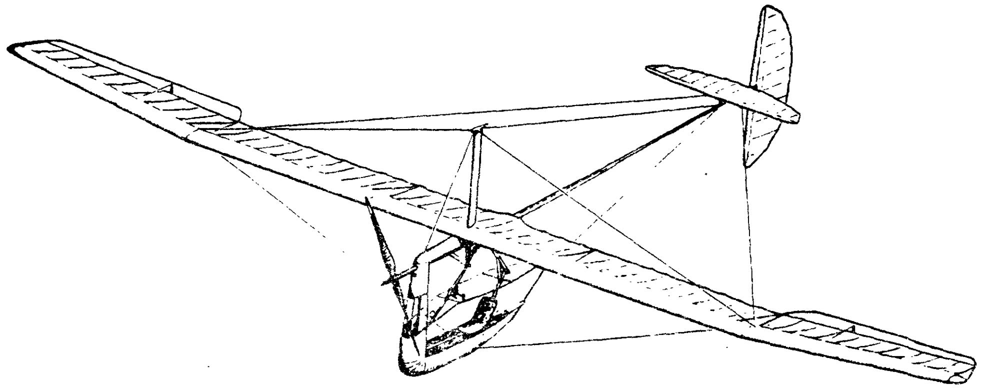
At first glance the new competition appeared to be almost too easy. Assuming a 10% increase in the course length (to 1650m) to allow negotiation of the triangular course, a lift-to-drag ratio of 20, and an aircraft weight (with pilot) of 950 N (210 lb), the energy required to climb three meters and fly the course is approximately 81.2 kJ. Allowing for a propeller efficiency of 90%, approximately 90.5 kJ would thus be required at the propshaft. The power available from the pilot depends on age, training, and motivation, but Whitt and Wilson (2) indicate that 250 W (.33 HP) could easily be obtained for the 13-minute duration involved, and levels up to 400 W (.54 HP) might actually be available during the flight. With 250 W provided for 9 minutes during the charge, the efficiency required from the energy-storage system was only about 30%. This efficiency could be achieved by a variety of systems, including electrical (batteries), mechanical (flywheel), and strain (rubber) energy storage.

Based on the encouraging initial calculations, we set out in late May to design and build an aircraft for the competition. Primary design considerations included the understandings that a) the project (both facilities and manpower) had to be completed before the fall 1983 academic semester began, and b) only limited funding would be available. Through July 1, 1983, students on the project provided all the funding. Thereafter, the Department of Aeronautics provided most of the funding. Total costs for the entire project ran to about $7300 (see (3) for a full discussion of the design process).

These considerations, coupled with concerns about potential competition from teams in California, Germany, and Japan, led to the selection of a "minimum" design that could set the record but probably not break it, could be built quickly near MIT, and would have minimum cost. The final design was a tractor monoplane with an aft tail, one pilot, and wire-braced aluminum tube construction. Two versions of the aircraft were eventually built: the "A" version that made 29 flights during the summer of 1983, and a "B" version that made 35 flights during the spring of 1984 and set the speed record. The two versions were very similar and used most of the same parts, the B version differing by its use of recumbent pilot seating, the addition of ailerons, and the use of an actively-controlled variable-pitch propeller (see Figure 1).

III. Aerodyhamic Surfaces

The wing was a 18.75m- (62 ft-) span wire-braced monoplane. Since neither the project's schedule nor budget allowed the use of graphite-epoxy, the primary structure was entirely 6061-T6 aluminum tubing. A single 6.35-cm (2.5-in) o.d. spar located at the 29%-chord point carried the lift loads. The spar had .89mm (.035 in) walls in the center panels, but tapered to .46mm (.018 in) at the tips (the spar was tapered by chemical milling, which we performed in a one-day special operation). Designed for a yield load of 2.0 *g*'s, the outer 3.7m (12 ft) panel of the spar was fully cantilevered. A single 1.09-mm- (.043-in)- diameter steel wire attached at the dihedral break



carried the main lift loads. A single wire from the top mast was designed for 1.5-*g* downloads. The trailing-edge wire was sized to carry the forward loading encountered at high-lift conditions, while the leading-edge wire and main lift wire together carried aft bending loads. The wing was originally warped for roll control, but 9%-chord ailerons were added to the tip panels on the "B" version.

The airfoil was a modified Lissaman 7769, similar to the airfoil used on the *Gossamer* series of aircraft and on *Chrysalis*. Ribs were constructed from 2.0-lb/ft foam, bought in blocks and sliced using a machine designed by Bob Parks. Each rib had top and bottom cap strips of graphite-epoxy. To prevent debonding, each cap strip was secured by a layer of .75 oz. fiberglass cloth. The leading edge was sheeted with 4.7-mm (3/16-in)-thick foam. The ribs were reinforced near the spar with .4-mm (1/64-in) plywood. Special angled ribs at the panel joints took both compression and covering loads. The wings were covered with half-mil tensilized Mylar, donated by DuPont.

Construction of the all-flying rudder and stabilizer were similar, except that these surfaces were fully cantilevered. The tail surfaces had 2.54-cm (1.0-in)-diameter spars and were covered with third-mil Mylar.

IV. Fuselage

The fuselage was built of aluminum tubing, with each joint machined to fit and then lashed with Kevlar roving. In the initial design the pilot was seated vertically, but in the "B" version recumbent seating was used. The seat itself was Kevlar cloth stretched over an aluminum frame. The pilot grasped a three-axis stick, with toggle switches on the stick for motor on/off and throttle control, and push switches for radio mike and manual control of prop pitch. The aircraft had a main landing gear beneath the pilot and a small wheel beneath the nose. Both wheels were fuly castored and shock-absorbing. A brake was included on the "B" version.

V. Propulsion System

After briefly considering flywheels (too complicated) and rubber (too heavy), we elected to develop an electrical-energy-storage system. In our judgement the relatively low efficiency (about 33%) was more than offset by the low development time and cost. The final system (shown in detail in Figure 1) consisted of: 1) standard bicycle cranks, driving a flexible chain; 2) a minimum-induced-loss tractor propeller, disconnected via a clutch during charging; 3) a 62.2:1 three-stage gearbox; 4) a 700-W DC motor (Geist type 60/28) normally used for electric model aircraft; 5) a power controller; 6) a bank of 1.2 A-hr NiCad batteries; and 7) a servo, pushrod, and control logic to vary the pitch of the propeller.

The key concept in this system was the idea of splitting the battery pack during charging. This allowed us to use the flight motor as the generator, and to do so without changing the gearing between charging and flying (the conversion could be accomplished in less than 10 seconds). We traded mechanical complexity for electronic complexity: a key element in the system was the power controller. Designed and built by Steve Finberg, the controller performed a variety of functions, including: 1) splitting the battery pack, automatically cycling between two subpacks every ten seconds during charging; 2) providing visual confirmation of charge cycling via LEDs; 3) providing a direct current between the batteries and the motor (the pilot turned the motor on and off via a relay, and the amperage readings were taken via a Hall-Effect device, without the losses of a shunt); 4) use of a current-sensing system to act as a no-loss diode; and 5) sensing battery-pack voltage and providing an audible low-voltage alarm.

Performance of the propulsion system is illustrated in Figure 2. Curves of motor performance (power produced versus rpm and voltage) are plotted along with propeller performance (power absorbed versus prop pitch and rpm) for a given flight speed. If the pilot produces no power, the system will operate at the intersection of the appropriate voltage and prop-pitch curves. Once the pilot pedals faster than the corresponding rpm, he adds power to the system. At the contest operation point, the pilot produced approximately 75% of the total power.

Initially the voltage and the prop pitch were variable only on the ground. This produced serious problems during the initial flight program: when the pilot increased his output power, only a fraction was delivered to the propeller while the rest merely unloaded the motor. This was solved on the "B" version by the introduction of a variable-pitch propeller. By coupling the current-sensing feature of the power controller to additional electronic logic, an active-control system was developed that would maintain a selected motor current at all times by making appropriate adjustments to the propeller pitch. Not only did this uncouple the motor's output from the pilot's, but it provided a convenient throttle and thus a means of rationing the electrical energy for optimum use throughout the flight. The pilot was provided with a two-position electronic "throttle" providing him with "climb" and "cruise" power settings, and the exact current associated with each throttle setting was adjusted between flights through potentiometers.

VI. Flight Program

Monarch made its first flight on August 14, 1983 with Rick Sheppe at the controls. A certified flight instructor, Rick was not a trained athlete and was never intended to be the pilot for the record attempt. Unfortunately, the pilot/athlete who had been training crashed the aircraft on his second flight, on August 19. The aircraft was repaired and flying again by September 2 with a third pilot, Frank Scarabino. Between September 2 and September 23, 1983, Scarabino made 25 flights, including several attempts with observers to fly the qualifying course. Pressures from MIT's fall academic semester, however, led to a curtailment of activity, and after the MacCready *Bionic Bat* team claimed the record on September 25 (see Part VII), the *Monarch* was disassembled and stored for the winter.

The spring 1984 test program included 35 flights, all by Scarabino. The first flight of the "B" version was made on April 3, 1984. On April 30 the *Monarch* completed its qualifying flight, and on May 5 Scarabino missed the Kremer prize by .43 seconds. On May 11, 1984, Scarabino flew the course in 00:02:49.7, claiming the speed record and, as noted by *New scientist*, "adding a new name to the rolls of the Kremer Prizes". At the end of the charge period the door zipper had jammed, so Scarabino crossed the starting line 00:10:05 after commencement of the energy storage. The five seconds were added to the flight time, and on July 20 the Man Powered Aircraft Group of the RAeS certified the record at 00:02:55. Following review and approval by the RAeS Prize Committee, the Governing Council of the RAeS voted on September 27, 1984, to declare the *Monarch*'s flight official and to award the 20,000 first prize to MIT.

VII. Competitors

The race for the Kremer World Speed record was the closest human-powered-aircraft competition yet. A team under the direction of Paul MacCready (winner of the first two Kremer prizes) built an entry known as the *Bionic Bat*. The *Bat* filed a claim on the Speed Prize in September 1983, but the claim was rejected by the RAeS in November, 1983, on the grounds that the rules concerning the energy-storage system had been violated. MacCready renewed his attempts on the record in January, 1984, and made continued design changes to the aircraft throughout the first half of

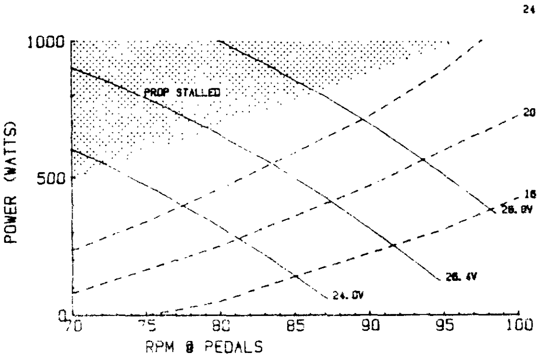


Figure 2 - Operating map of the Monarch *propulsion system for a flight speed of 22 mph. Solid curves represent motor performance; dotted lines, prop performance.*

MIT Monarch *team posed in front of the record-setting human-powered machine. Left to right are: John Langford, Jim Wilkerson, Tidhar Shalon, Mark Drehla (holding glass), Steve Finberg, and Frank Scarabino.*

1984. On July 20, 1984, the *Bionic Bat* team filed a claim for the 5000 second prize in the Kremer Speed Competition, although at the time of this writing (10/84) that claim has not been approved. In addition, a team in Germany built an aircraft known as the *Musculaire*. In June, 1984, the *Musculaire* claimed a £10,000 prize offered by the RAeS to the first non-American entry to fly the Figure-Eight course, and later in the summer (with an energy-storage system added) filed a claim for the third prize in the Kremer World Speed Competition. Even after the first three prizes have been awarded, some £70,000 will remain in the Speed Prize fund, although it remains to be seen whether the plans to disburse it in £5000 increments will attract additional competitors.

VIII. Conclusions

The *Monarch* is clearly a transitional aircraft. It is no longer a fragile gargantuan and yet neither is it a "practical" ultralight aircraft in any sense of the concept. Using nearly two orders of magnitude less power than present-day ultralights, *Monarch* illustrates the potential efficiencies that may be gained through technical sophistication.

The two great strengths of the *Monarch* design were its sizing and its propulsion system. From the beginning, the aircraft was properly sized to the task at hand. The propulsion system marked the first real use of advanced avionics on an HPA, and conclusively demonstrated the potential reductions in pilot workload and increases in system efficiency.

The *Monarch* was an educational experience for all those involved with it. It showed once again how well-matched human-powered aircraft are to the university environment: small enough to be manageable and yet sufficiently complex to test all aspects of an engineering education.

Acknowledgements

The list of people who contributed to this all-volunteer project is very long, and any list will be incomplete. We are particularly indebted to: Allan R. Shaw, who supported the project from its earliest days; Professors Walt Hollister and Ed Crawley, who served as faculty advisors; Professors James Mar and Jack Kerrebrock, who provided Departmental support and funding for the materials; Dr. Francis Low and Mr. John Tylko, who provided additional financial support; Chip Collins and his team of observers; Ed Becotte and his crew at the Lincoln Flight Lab Facility; and Frank Hidinger and Jim Merageas of MASSPORT and the FAA, respectively. Finally, we wish to acknowledge the volunteer help of many friends during the construction and flight program, including: Dave Akin, Paul Bauer, Mary Bowden, Monica Bullebach, Steve Bussolari, Scott Causbie, Scott Clifton, Juan Cruz, John Flynn, Whitney Hamnett, Geoff Landis, Barbara Langford, E E Larrabee, Tidhar Shalon, Sean Tavares, Jim Wilkerson, David Gordon Wilson, Don Weiner, and Guppy Youngren.

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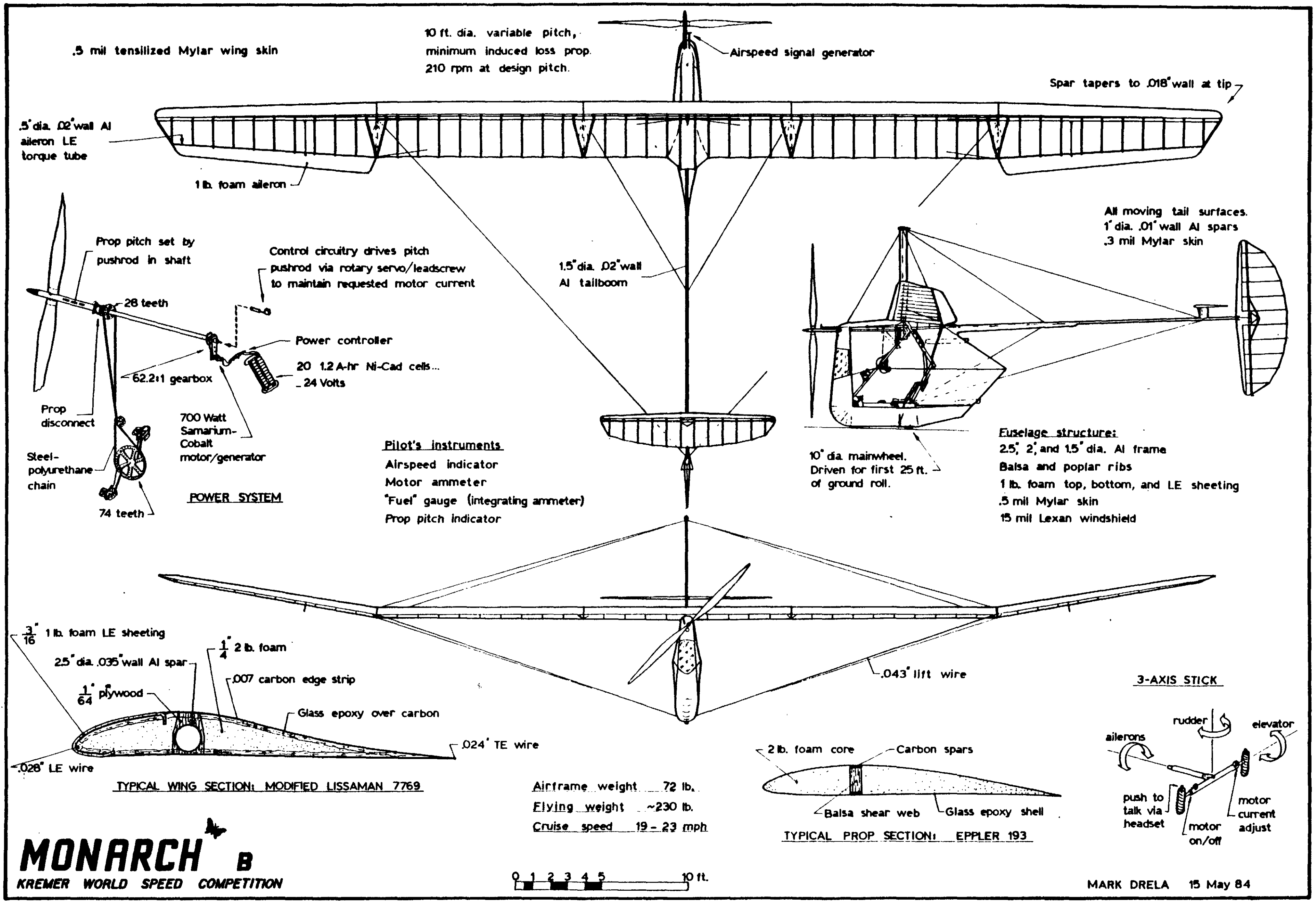
.5 mil tensilized Mylar wing skin
10 ft. dia. variable pitch,
minimum induced loss prop.
210 rpm at design pitch.
Airspeed signal generator
Spar tapers to .018" wall at tip
.5" dia. .02" wall Al
aileron LE
torque tube
1 lb. foam aileron
Prop pitch set by
pushrod in shaft
28 teeth
Control circuitry drives pitch
pushrod via rotary servo/leadscrew
to maintain requested motor current
Power controller
20 1.2 A-hr Ni-Cad cells...
24 Volts
62.2:1 gearbox
Prop
disconnect
700 Watt
Samarium-
Cobalt
motor/generator
Steel-
polyurethane
chain
74 teeth
POWER SYSTEM
1.5" dia. .02" wall
Al tailboom
Pilot's instruments
Airspeed indicator
Motor ammeter
"Fuel" gauge (integrating ammeter)
Prop pitch indicator
All moving tail surfaces.
1" dia. .01" wall Al spars
.3 mil Mylar skin
10" dia. mainwheel.
Driven for first 25 ft.
of ground roll.
Fuselage structure:
2.5", 2", and 1.5" dia. Al frame
Balsa and poplar ribs
1 lb. foam top, bottom, and LE sheeting
.5 mil Mylar skin
15 mil Lexan windshield
3/16" 1 lb. foam LE sheeting
2.5" dia. .035" wall Al spar
1/4" 2 lb. foam
.007 carbon edge strip
1/64" plywood
Glass epoxy over carbon
.024" TE wire
.028" LE wire
TYPICAL WING SECTION: MODIFIED LISSAMAN 7769
.043" lift wire
3-AXIS STICK
rudder
ailerons
elevator
push to
talk via
headset
motor
on/off
motor
current
adjust
2 lb. foam core
Carbon spars
Balsa shear web
Glass epoxy shell
TYPICAL PROP SECTION: EPPLER 193
Airframe weight 72 lb.
Flying weight ~230 lb.
Cruise speed 19 - 23 mph
0 1 2 3 4 5 10 ft.
MONARCH B
KREMER WORLD SPEED COMPETITION
MARK DRELA 15 May 84