The Muscalair 1 & 2 Human-Powered Aircraft and Their Optimization

E. Schoberl (translation. by Heinz Altherr and Dave Wilson)

MUSCULAIR 1 and 2 Human-Powered Aircraft

The era of human-powered aircraft began over fifty years ago with the 235 m flight of Haessler Villinger's "Mufti". When Henry Kremer offered his prize in 1959 for a one mile flight over a figure-of-eight course, it took almost two decades, and major developments in materials, technology and methods, for the prize to be won. Bryan Allen succeeded in completing the one mile figure-of-eight course first, in 1977, in Paul MacCready's Gossamer Condor, and conquered the English Channel in 1979 in the Gossamer Albatross, making two incomparable milestones in the history of flight.
Without the extremely light and high strength composite fiber materials, films and pressure-resistant foams, and without the aid of computer-developed high-lift-drag airfoil profiles and the high efficiency propellers designed by Prof. Larrabee, these developments would not have been possible.

The MUSCULAIR team and its concept.

Encouraged by the remarkable successes of solar aircraft development, and stimulated by MacCready's work, Gunter Rochelt, from Munich, and his friends announced the start of a human powered aircraft project in 1984 and set out to win the figure-of-eight Kremer prize still available to non-Americans, and the Kremer speed prizes, the third series of prizes Henry Kremer had offered. A basic concept was quickly decided upon: a conventional unbraced high-wing monoplane with laminar flow profile airfoils, a fully

profiled faired hanging cabin, a balanced rudder and a pusher propeller. The machine would have to be constructed of the lightest possible materials, with very high profile accuracy and surface finish in order to attain the highest possible speed with a minimum power requirement. The plane had to combine excellent stability with good controllability in order to give the pilot precise control while simultaneously putting out his maximum power. These contrary requirements seemed at first to be irreconcilable.

The task was all the more interesting because Rochelt's seventeen-year-old son, only an average athlete, had to win the speed prize without the aid of energy storage (which would have been allowed under the Kremer rules). Only with the most careful optimization of the aerodynamics, ergonomics, method of construction, flight and meteorological conditions would this be attainable.

The power requirement of an aircraft depend essentially upon the drag of the aircraft components, the induced drag, and the propulsion efficiency. The drag of the aircraft itself can be kept small by employing a low drag profile, especially one with laminar flow over much of the airfoil, by small surface areas (wings and controls) and by the avoidance of flow disturbances. The induced drag can be minimized through the use of the smallest possible all-up weight, a large wing span, high flight speed, and the best approximation to an elliptical lift distribution.

The propulsion efficiency can be improved through the use of a low-loss power transmission and the largest possible slow-running propeller.

The wing design

Since the profile and induced drag amount to about 85 percent of the total drag, a favorable wing configuration is particularly important.
In order to optimize the wing design it is essential that the following must be considered: 1) the choice of airfoil section and the Reynolds no.; 2) the wing surface area and aspect ratio; 3) the lift distribution; 4) the minimization of the low speed flight power requirements to about 200 watts; 5) the use of the highest possible flight speed; 6) a wing mass to give the highest strength and stiffness; and, 7) the most favorable stall behavior, forgiving flying characteristics, and good controllability (fast response of the total airplane to rudder movements).

The results of many trial calculations (figure 1) showed that in the total region of human powered flight from low speed, long duration flight, to short time, high speed flight, the most favorable span and thickness distribution was given by a trapezoidal wing with a laminar flow profile. In this way we arrived at an aircraft weight of 750 N for a small, fast plane to 850 N for a larger and slower craft, attainable with a light pilot and careful lightweight construction without the use of external bracing wires.
The wing span should not be allowed to increase much over 22m, since above this dimension the power requirement reduces only insignificantly, and the aircraft becomes hard to control because of its increased moment of

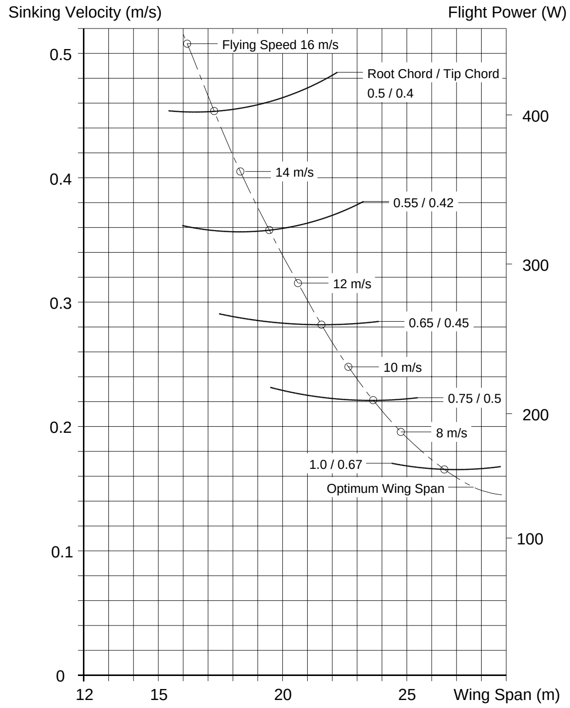


Fig.1 Minimum Sinking Velocity and Power Requirement and Optimum wing Configuration of Marn-Powered PlanesFig.1 Minimum Sinking Velocity and Power Requirement and Optimum wing Configuration of Marn-Powered Planes

inertia, even with extremely lightweight construction.

We chose for the airfoil profile the laminar shape termed FX 76 MP (man-powered), developed by Prof. F. X. Wortmann in 1976 for human-powered aircraft, figures 5 & 6. This was thought to be one of the best profiles in the Reynolds number region of about 500,000, as it develops nearly maximum lift over a wide range of lift coefficient (Cf = 0.7 to 1.2) despite the unavoidable profile variations that must accompany ultralight construction techniques, thus retaining its good-natured characteristics.

MUSCULAIR 1 as an all perpose aircraft

.

Musculair 1 was conceived as an all-purpose aircraft to win both the Kremer figure-of-eight and the speed prizes without resorting to energy storage. In the course of optimization calculations it became quickly obvious that the valuable aerodynamic concept and the wide operat-

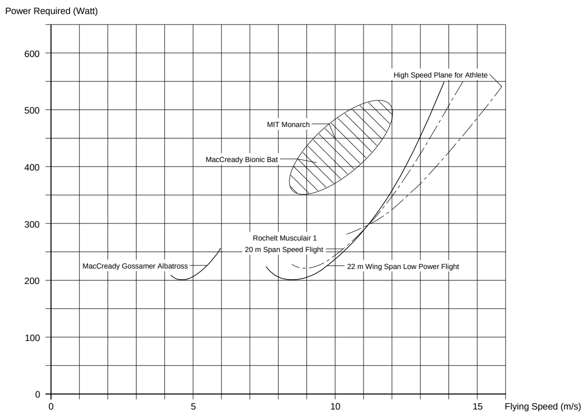


Fig. 2: Power Requirement of Man powered Planes

ing range of laminar flow profiles enabled both projects to be tackled with the same wing profile. In low speed flight the lift coefficient was, at about 1.2, in the higher region of minimum profile losses; and in high speed flight, with Cf=0.75, in the lower region of minimum losses (fig.5).

For transportation reasons the wing was made in six parts, of which the main spar, designed for three times the static load, weighed only 8 kg. To avoid irregularities in the laminar flow region the upper surface of the wing back to about 60 percent chord is covered with 4mm thick Styrofoam. The remainder of the surface is covered with Mylar film. Profile measurements on a finished wing section were conducted by Dieter Althaus in a laminar wind tunnel at the University of Stuttgart, and confirmed the good profile. It was found that it was the fine roughness of he Styrofoam surface that just brought about laminar-turbulent transition at the point wanted without a laminar separation bubble. This reduced the airfoil drag by about 10 percent.

Aircraft structure

The main structural elements of the fuselage are the vertical main tube and the stabiliser strut in which the propeller shaft rotates. All components are made of carbon-fibre-reinforced composites. The relatively large cabin is faired to conform to the relatively insensitive NACA 64021 profile. The self-centering ailerons and rudder are Mylar-covered and have a surface area considerably larger than required to achieve high flight stability. A pair of springs keeps the rudder in a neutral position and thus eases the control for the pilot.

The pedal-power train, which weighs only 450 g (in racing bicycles 1.2 kg is normal), transmits the power through a fine chain to the carbon-fibre propeller shaft, supported in four bearings, and back to the 2.72m diameter pusher propeller. At barely 100 pedal rpm, the propeller runs at 230 rpm. The pusher propeller, developed in 1980 for a solar aircraft, has been modified for the special conditions of human powered flight, but still has over 86 percent efficiency (see figure 9).

Controls

The control problem has been solved very elegantly, economically and ergonomically. While a road racer forms a fixed unit with his bicycle and force is transmitted between the hands and the handlebars as well as between the feet and the pedals, the HPA pilot must keep his/her body almost immobile above the hips to allow the controls to be handled sensitively. Precise control is more important than the absolute maximum in power output. That a pilot experienced only in flying hang-gliders was able to control the craft at the first attempt, can be attributed to the ergonomically designed joystick, which actuates all three control surfaces. When steering, the pilot has only to envision that he holds the wingtips with his hands, and twisting of the control surfaces will cause the plane to perform the desired maneuvers. Sideways tilting of the control stick operates the ailerons, rotation about a vertical axis acts upon the main rudder, and rotation of the handgrips in the same way as opening the throttle of a motorcycle acts on the elevators. A co worker experienced only in mode airplane flying achieved a 500 m clean flight on his first attempt.

First goal achieved: The figure-of-eight prize

During the three month period of construction of the aircraft, the pilot completed a training program set up by the Sports College of Munich. The first hop was accomplished at the Munich Military Airport at Neubiberg at the end of May, 1984. It was done without fairing on the pilot cabin. At the end of only

two weeks of training, on June 18, 1984, the flight over a one mile, figure-of-eight course was achieved in 4 min. 5 seconds, almost twice as fast as Bryan Allen's flight in MacCready's Gossamer Condor in 1977.

The second goal: The Kremer speed prize

To also win a Kremer Speed Prize, the first of which meanwhile had been won by the Monarch student group from MIT, it was necessary to improve upon the previous speed by more than the required five percent, and the plane had to be aerodynamically refined and optimized. As a result of the test flights the pilot learned to fly the plane perfectly. Meanwhile, MacCready with the Bionic Bat had won the second Kremer speed prize by improving on the MIT speed by more than five percent. Both teams used energy storage and hence had approximately twice the peak power available (figure 2).
On August 21, 1984, pilot Holger Rochelt, in optimum conditions, flew the speed course in 2 min 31.38 seconds, improving MacCready's speed by 7 percent, and for the first time established a speed record for human powered flight without energy storage.

The first pasenger flight!

Musculair 1 became an attraction at a few air shows and surprised everyone by demonstrating the astonishing manoeuvrability of such a large aircraft.

To test the available reserves of the pilot and aircraft, and to close off the 1984 flying season, Holger Rochelt on the last flight took along as a passenger his sister Katrin who, at 28kg, weighed exactly the same as the bare airplane.

So on October 1. 19

The end of MUSCULAIR 1 and the birth of a high speed successor

When in the spring of 1985 Musculair 1 was involved in a traffic accident on the road and was heavily damaged, the idea arose of building an aircraft purely for high speed flight. The large reserve capability and the good natured flight characteristics of the all-round Musculair 1 led to the expectation of a significant increase in performance. The author's calculations showed that by designing purely for speed, a time of 2 minutes, which is 45 km/h (12.5 m/s) for the first 1500m course, would be achievable without energy storage. This speed is significantly higher than the new MacCready speed of 37.7 km/h (10.5 m/s) of Dec 2, 1984. Based on the knowledge of the successful Musculair 1, the construction of Musculair 2 (figure 4) was relatively simple. Since proven concepts had only to be adapted for fast flight, we merely had to reoptimize the aerodynamics, mechanics and construction methods for the new conditions. The aerodynamicist Dieter Althaus of the University of Stuttgart modified and optimized the successful Wortmann profile FX 76 MP precisely for the high speed conditions (lift coefficient 0.8 at Reynolds numbers of 600,000 inside and 400,000 outside) without reducing its good characteristics. To avoid torsional problems as were experienced in Musculair 1, and to achieve the accuracy and surface finish required for the laminar profile, the wings were covered with a 3mm foam/fiberglass sandwich, and then covered with Mylar film (figure 7). The 4 kg. main carbon-fibre-reinforced spar was made in four pieces, and was designed for three "g". Through the special design of the wing tips, the intensity of the wingtip vortex, and hence the induced resistance, was slightly reduced.

Semi-recumbent pilot position and elliptical chainwheel.

The semi-recumbent position of the pilot was expected to result in an improved energy balance. The pilot cabin could be made smaller and held to a truer profile through the use of a super

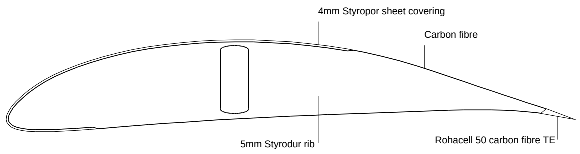


Fig 6. Wing structrure of Musculair 1 with Wortman FX 76 MP (man powered) airfoil.

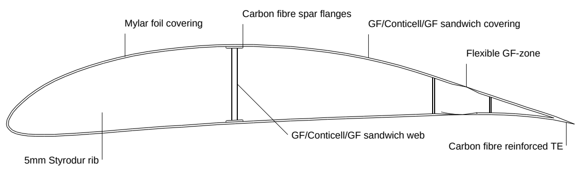


Fig 7. Wing structrure of Musculair 2 Wortman airfoil FX 76 A, modified by D. Althaus.

light fiberglass sandwich fairing. We have no yet established the optimum sitting position of the pilot at which he could deliver high power and yet is able to pilot accurately.

The pedal power output was improved by about 5 percent through the use of an elliptical chainwheel. Proven components like the controls, the rudder configuration, and the pusher propeller were used without modification.
With a multitude of clever solutions, Gunter Rochelt was able to realize a very simple clean construction which was functional down to the last detail and highly efficient aerodynamically. With the most economical use of materials, and an almost stingy application of epoxy resin, the Musculair 2 weighed, ready to fly, 24 kg (figure 4). At the very beginning of the flight tests in September 1984, it was apparent (not really unexpectedly) that the airplane, in contrast to the good-natured Musculair 1, could be flown safely only with a fast powerful flight of about 250 watts pedal input, and then was very sensitive to control inputs. Shortly afterwards Musculair 2 was heavily damaged in a crash landing at an air show, but was rebuilt in a little over a week.

A new Kremer prize

Unusually beautiful fall weather allowed continuation of the test flights. On October 1, 1985, Rochelt achieved a new speed world record of 2 minutes 21 seconds at the airport of Oberschleissheim, near Munich, but could not better MacCready's speed by the required five percent. On the following day, a bicycle racer started working on the pilot two hours before the start to get him physically and psycologically ready for the tough job ahead, and brought him into super form. The course selected was a long loop over the runway such as to make best use of the minute early evening thermal lift. Hence, Holger Rochelt was able to increase, under the most favourable conditions, the world speed record and the Kremer speed prize to 2 minutes and 2 seconds, or 44.26 km/h (12.3 m/s).

Recommendations for the future of human powered flight

Nobody had expected this vast improvement from an amateur team unsupported by any large, wealthy sponsor. It would be difficult to improve upon this achievement with justifiable effort without resorting to energy storage. If one evaluates the possibilities of improvements in aerodynamics, aircraft technology, ergonomics and flying techniques of fast flight, it seems that without energy storage 50 km/h, approx. 14 m/s, is already achievable, and 100 seconds for the 1500 m course is certainly reachable. With aerodynamically sophisticated ultralight construction methods, one can build relatively small and yet superlight human powered aircraft for endurance and for long distance flight, that can fly with less than 200 watts, approx. 0.25 hp, and at almost 30 km/h, 8.3 m/s. This kind of airplane, similar to the Musculair 1 concept, but with many improved details, with a wingspan not over 24 m, can be built with 30 kg total weight, such that it is easy to control and has good-natured flight characteristics. Because of the higher flight speed, this type of airplane does not react so sensitively to gusts, and can make headway even against light headwinds. For the Daedalus project, for which the 96 km stretch from Crete to the Greek mainland has to be conquered, this is especially important, since in the Aegean Sea one has to be prepared for sudden winds, one of the reasons why this area is also a famous sailing region. An airplane built for the Daedalus project should preferably be designed for barely 30-km/h cruising speed at approximately 200 watts power requirements rather than for minimum power requirements at slow speed, approx. 150 watts at 23 km/h, so as not to be doomed by an upcoming light head-wind.

The development of human powered helicopters is, because of the high power requirements and the stability and control problems, very difficult. The author calculated a minimum rotor power requirement at low rpm without lift at about 200 watts. That power for example was sufficient to enable the MacCready Gossamer Albatross or the Musculair 1 to fly. Even at low flight alttude and with the strong help of ground effect, the power requirements would be nearly doubled, such that the author does not think that it would be possible to have long or high helicopter flights. It therefore does not seem to be likely that anyone will achieve a breakthrough in the near future, a circumstance which is a large challenge for real enthusiasts.

MUSCULAIR technical data

PLANE	MUSCULAIR 1	MUSCULAIR 2
Type	HP all-purpose	HP speed plane
Builder	Gunter Rochelt. Munchen, W. Germany	
Construction	High-wing monoplane with rear prop.	
Span	22m (20m for speed)	19.5m
Length	7.1m	6.0 m
Fuselage height	2.12m	1.5m
Wing area	16.5	11.7 sq. m.
Aspect ratio	29.3	32.5
Airfoil	Wortmann FX76 MP root 16% thick tip 14% thick	FX76 MP modified by Dieter Althaus
Empty weight	28 kg	25 kg
Flying weight	82 kg (with passenger 110 kg)	78 kg
Wing loading	49 N/sq.m.	65.4 N/sq.m.
Min.flying speed	7.5 m/s	10.0 m/s
Min. power at speed	200 W @ 8.5 m/s	250 W @ 10 m/s
Full power at speed	265 W @ 1 I m/s	315 W @ 12 m/s
Min. sink rate	0.22 m/s	0.27 m/s
Max. glide ratio	1:38	1:37
Propeller	Solair 1 mod.	
	2.72m dia.	2.68m dia.

Materials for both: "Sigri" carbon fibre "Rohacell" foam "Styrodur" foam "Conticell" foam "Bakelite L20" epoxy resin "Mylar" film.

Propeller data for MUSCULAIR 1

Modified from the propeller designed for the SOLAIR 1 aircraft

computation and design E Schoberl. Minimum induced loss design for operation in turbulence as rear prop

`	design data for solair 1 (measured values)	modification for musculair 1
Diameter	2.65 m	2.72 m
pitch	2.5 m	
Thrust	120 N	21 N
Flying speed	11.7 m/s	8 m/s
Power absorbed	1700 Watt	195 Watt
Efficiency	82%	86%
Pitch adjustment		-1.5 degrees

The Kremer influance

The prizes donated by the British industrialist Henry Kremer were a great worldwide incentive for the development of many human powered aircraft. They gave new impulses to the largely neglected area of low speed aerodynamics between model airplanes and gliders, and to the precise design of high strength. ultralight construction. They also helped to develop the technology required for unmanned aerodynamically highly efficient ultralight aircraft with solar or hybrid power, which can remain aloft in the stratosphere for weeks or months and can be used for example for the economical transmission of news.

Ernst Schoberl Ossiacher Strasse 42 D-8500 Nurnberg 50, West Germany.

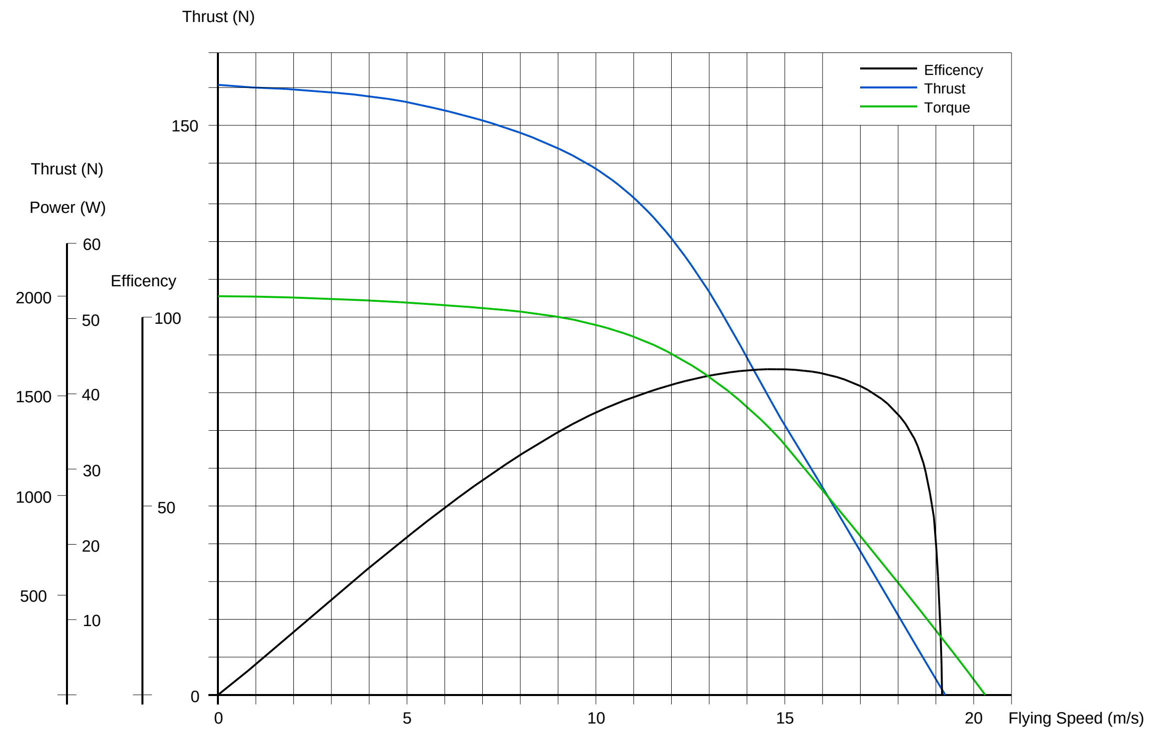


Fig 9 Propeller operation graphs at 360 rpm (wind tunnel test)

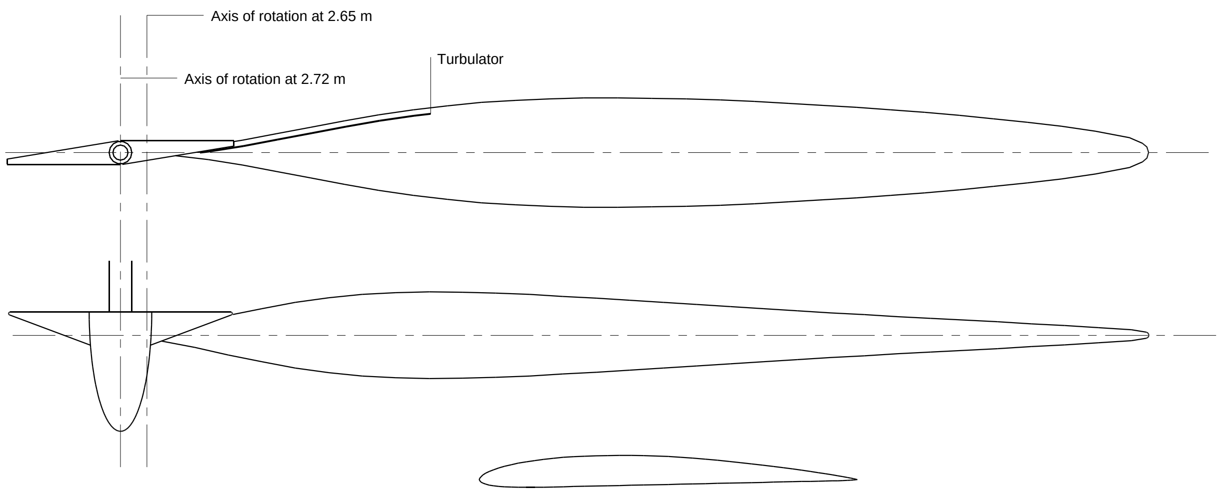
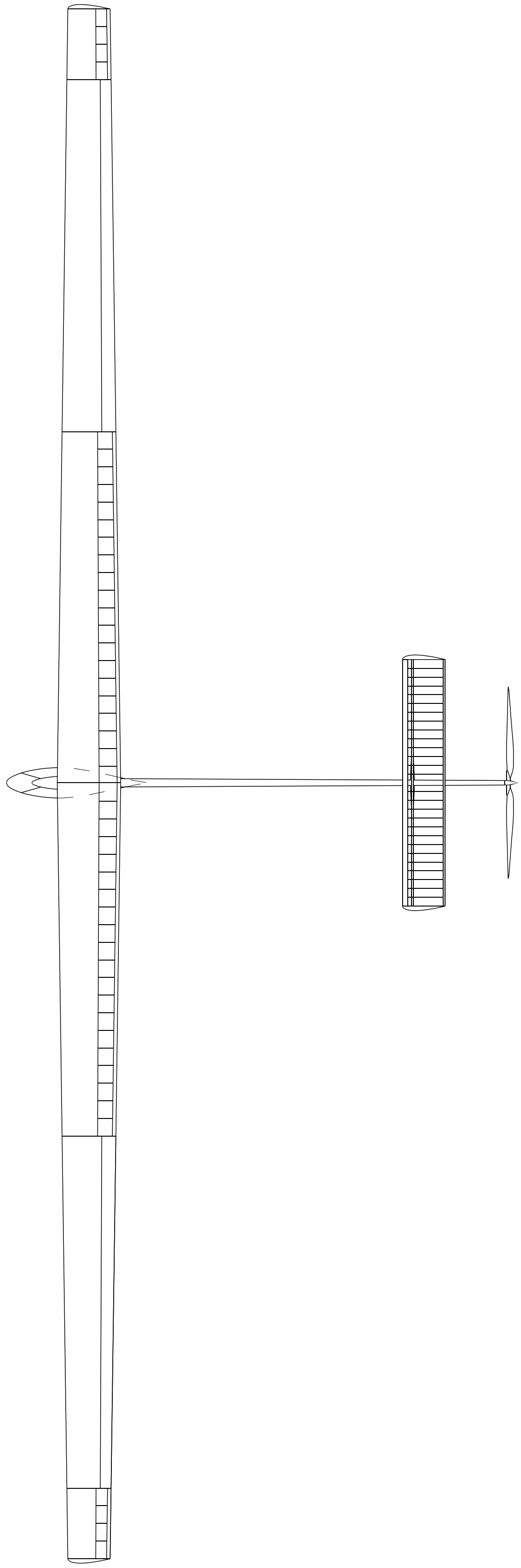


Fig.3 MUSCULAIR 1



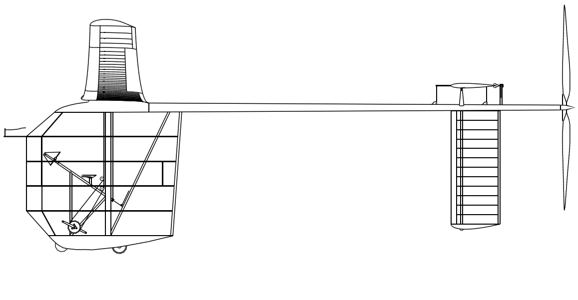


Fig.4 MUSCULAIR 2