

# PHOENIX A Polyester-Film Inflatable Man-Powered Aircraft by F.E. To

*Frederick To, AMRAeS was born in Hong Kong in 1938, came to the UK in 1952 to study, and qualified as an architect. He joined the RAeS in the early 70s, his main interest then was man-powered flight. In 1974 he made a documentary film on the subject called "The Last Challenge". He started building Solar One with the help and advice of David Williams in 1977 The next year Solar One made its first short hop at Lasham and it is believed it then became the world's first solar powered aircraft. By the middle of 1978 Fred To was making structural tests on the use of polyester film structures for an inflatable wing. He designed and built 'Phoenix,' the success of which is illustrated in this paper. He also tried unsuccessfully to produce an inflatable microlight, a project which was hampered in mid-life by the introduction of CAA regulations. In 1980 he formed his own company, The Air-Plane Co to undertake inflatable aircraft powered by a 22 hp engine. He still practises as an architect.*

## Abstract

This paper describes some of the design solutions adopted in solving two major problems besetting man-powered aircraft in use: that of breakage and storage. It describes work leading up to the building and testing of "Phoenix", a man-powered aircraft with a polyester-film inflatable wing. The paper deals mainly with aspects relating to the wing design and construction.

## The problem

The Kremer Prizes for man-powered aircraft set up in 1959 in the UK generated considerable interest worldwide. For 17 years various groups and individuals designed, built and flew over 30 aircraft but failed to collect the prizes. Due to the low power output of man - about 1/3 hp, aircraft weight has had to be kept to a minimum, resulting in complicated and extremely fragile structures. In order to capitalise on the reduction of induced drag due to ground-effect, up to now these aircraft have been forced to fly at about 10ft above the ground. With

insufficient spare power to control these aircraft so close to the ground crashes are all too frequent, leading to considerable time being spent in repairing structural damage. Another practical problem besetting the constructor and operator of man-powered aircraft is that of storage and construction space. Wingspans of around 90ft for aircraft attempting the figure-of-eight Kremer Prize are normal, and at least three aircraft with wingspans of over 130ft have been built. Finding hangars for these aircraft is a constant problem. (A new generation of aircraft with a smaller wingspan is now being encouraged.) The arrival of the "Gossamer Condor", designed by Paul McCready, demonstrated that the repairs problem could be greatly alleviated, but the aircraft still suffered damage in crashes. With the crossing of the English Channel by the "Gossamer Albatross" in 1979 man-powered flight had reached a significant state of maturity. These two aircraft set a new trend in motion, but the problems of storage and crashability still remained.

## The Solution

The late Dan Perkins, an engineer at the Royal Aircraft Establishment at Cardington, had identified these two problems in the early 60's and attempted to solve them with designs using inflatable wings. He built four of these inflatable-wing man-powered aircraft; the last, "Reluctant Phoenix" (Fig 1) proved most promising.

The aircraft was a delta flying-wing with a wingspan of 31 ft and an empty weight of 391b. The envelope of the wing was made of polyurethane-coated nylon fabric. Due to the high power requirement for cruise, the aircraft was limited to short hops under man-power as it was being flight tested inside an 800ft long airship hangar. About 90 flights were made. "Reluctant Phoenix" was successful in that it could be folded away and transported in the back of a small station wagon. It also survived many crashes without requiring repairs as the aircraft merely bounced when in collision with the ground. Shortly after Perkins' death the "Reluctant Phoenix"

was handed over to the author, who immediately recognised the advantages of the system. The Air-plane Co Ltd was formed and development work began in 1978.

## Development work: a prototype wing

As polyurethane-coated nylon fabric is a relatively expensive material it was felt that polyester-film might offer the same

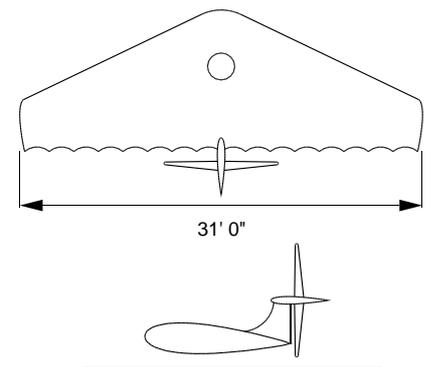
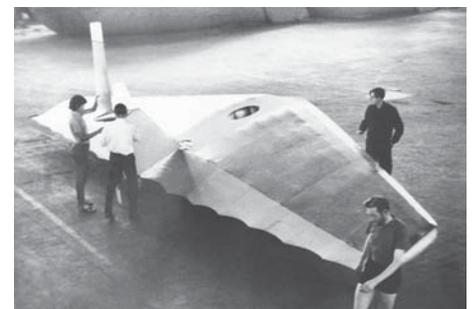


Fig 1. Reluctant Phoenix



Inflating Reluctant Phoenix



Reluctant Phoenix at Cardington

advantages at a much lower cost. The advantages of polyester-film being that it does not require a coating to make the material impervious to air. It offers good strength to weight ratio and is dimensionally stable.

## The Structure

Apart from the drop-thread system adopted by Goodyear in their development of an inflatable aircraft wing, there are two other basic approaches. (Figs 2 & 3). Method A consists of inflated cylinders of varying diameters attached to each other. An outer skin is stretched around this to enhance rigidity and to give a somewhat crude aerofoil shape. Accurate approximation of an aerofoil section is impossible with this system due to the large spacing of the inflated cylinders 1, 2, 3, 4 and 5. Torsional stiffness of the system is also low. The main advantage of this system is that it is simple to produce. A development of this system. Method B (Fig 3), is structurally stronger. An aerofoil section is drawn and within this is marked out overlapping circles to fit the aerofoil shape. Vertical webs are then placed at the junctions of each pair of adjacent circles and an outer aerodynamic skin is again stretched over the inflated envelope. It will be noted that this results in a closer approximation of the aerofoil shape desired, depending on the spacing on the web. Spanwise 'Flats' will always exist in the outer skin between each curved section. In a thin walled-inflated cylinder, tension along the perimeter of the circle is expressed as  $T = pr$ .  $T$  being tension,  $r$  being radius and  $p$  being pressure. Tension along the length of the cylinder being related to the cross-sectional area of the cylinder.

$$T_1 = \frac{\pi r^2 p}{2 \pi r} = \frac{pr}{2}$$

As the cross-sectional area of the inflated section within a given shape is greater in Method B, this system gives much greater rigidity torsionally. Method B also allows a closer matching of tensions in the envelope chord wise and spanwise, resulting in a reduced weight of fabric or film used. The aerofoil section adopted by Perkins was symmetrical and had a thickness of 20% chord with eight webs, Method B (Fig 3) being employed. As both the envelope and webs in Perkins' structure were in nylon fabric it was possible to stitch the envelope and webs together. The stitch-holes in the envelope being re-sealed with a brush-on grade of polyurethane. This proved successful in use. The forces in a typical web / envelope junction are

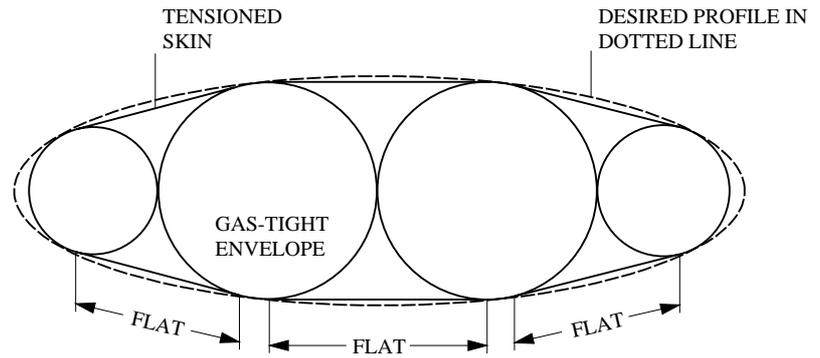


Fig 2. Method 'A'

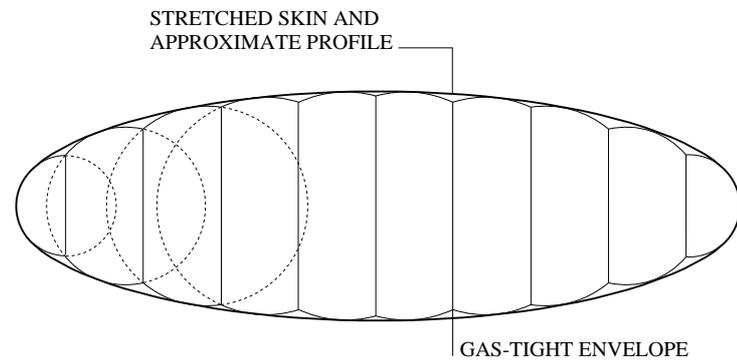
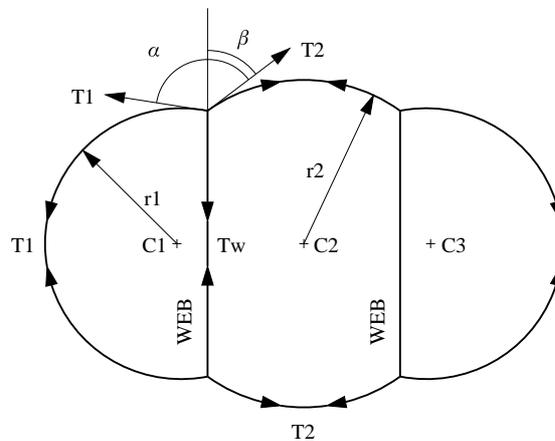


Fig 3. Method 'B'



$$\begin{aligned} T_1 &= r_1 p \\ T_2 &= r_2 p \\ T_w &= T_1 \cos \alpha + T_2 \cos \beta \end{aligned}$$

Fig 4.

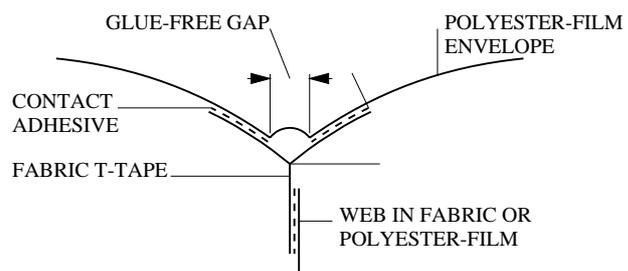


Fig 5.

as shown in Fig 4.

$$T1 = r1 p$$

$$T2 = r2 p$$

$$Tw = T1 \cos \alpha + T2 \cos \beta$$

### Bonding solution for polyester-film

The possibility of using various single sided and double-sided tapes at the crucial junction seemed attractive. But this proved impossible. The method that proved entirely satisfactory in the end was to have a "T" shaped tape made in nylon fabric which had two leaves glued by a suitable contact adhesive to the polyester-film envelope, with its remaining leaf glued to a polyester-film web or stitched to a fabric web. (Fig 5) A glue-free gap was built in at each junction to eliminate peeling should the "T" shape surface and the envelope film move relative to each other due to creep in the adhesive. It was found that the fabric used in the webs or "T" tape was easier to handle if it was stabilised by a coating of polyurethane. Normal practice for contact adhesives is to coat the two surfaces to be bonded and bring these surfaces together while the adhesive is still "wet". However, the impervious polyester-film and the coated fabric formed an effective seal to the adhesive once they were brought together, making it impossible for the remaining solvent to be released. A way round this problem was found. The process was to apply adhesive to both surfaces and allow this to dry off completely before the two surfaces to be bonded were brought together. This made it possible for fine alignment to be made as the adhesive was no longer "tacky". The glue was then reactivated by a hot iron, resulting in a permanent bond. With the bonding problem solved it was decided to construct a 20ft span model in 23 micron polyester-film. This took two weeks and proved successful.

### Design considerations: "Phoenix"

A flying wing configuration was chosen although this necessitated a reflex cambered aerofoil section resulting in higher profile drag and lower maximum lift coefficients. It was felt that the inherent simplicity of the inflatable wing in rigging and transportation would be lost if canards or tailplanes and a fuse-

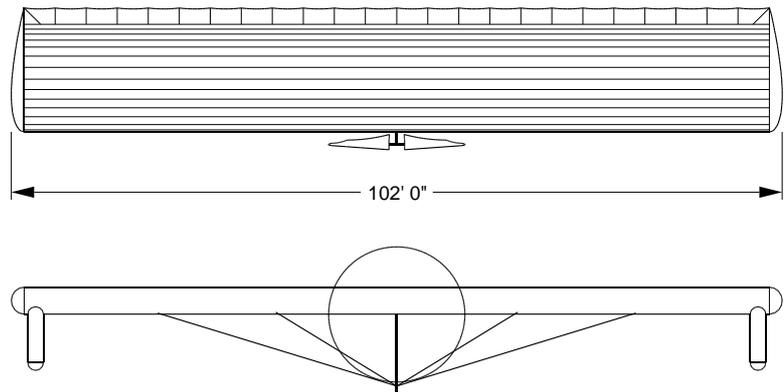


Fig 6.

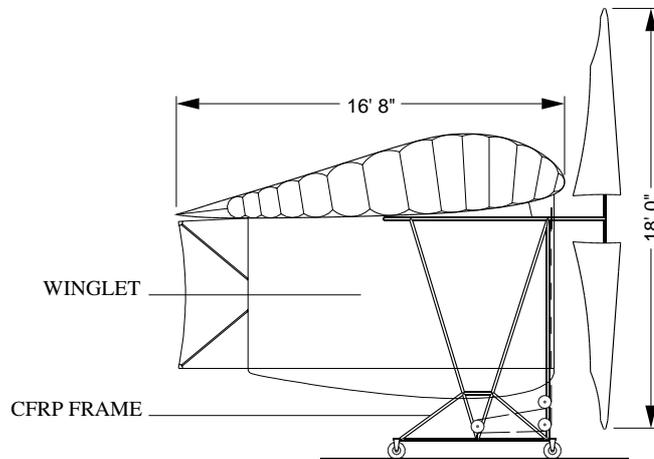


Fig 7.



20' span prototype wing for Phoenix

lage also had to be carried around.

**WING PLANFORM** - Although the "Reluctant Phoenix" and other man-powered aircraft usually have tapered wingtips. It can be demonstrated that this offers no advantages in the case of the inflatable structure as the tension in the envelope would decrease towards the wing-tip due to the reduced diameter of the cells. Furthermore. Man-powered aircraft operate at extremely low Reynolds numbers of around 500.000. With reduced chord at the tips due to taper. The Reynolds number is further reduced, resulting in higher profile drags at outer span. Lower max lift coefficients also accompany lower Reynolds numbers. The tapered wing therefore offers no advantage. A rectangular wing planform would facilitate manufacture as all glue lines would be parallel. Therefore the rectangular planform was adopted. (Figs 6 & 7)

An aspect ratio of 6 was considered to be the practical limit for pitch stability. The resultant design was an aircraft with a wingspan of 100ft and a chord of 16ft 8in and an aircraft weight of 851b, the power requirement being .33hp for cruise at 10ft ht at 8mph. (Until it could be verified by wind tunnel tests, profile drag coefficients of the "Flated" aerofoil were assumed to be approximately 25% higher than a comparable smooth surfaced wing.)

### Winglets

The wing, which had to be braced with flying wires. Had to be located 10 ft above the ground on a carbon fibre tubed pilot support structure. This meant that at a flying height of 10ft the wing would be 20ft above the ground, reducing ground-effect. A system of downturned winglets was adopted, the principle behind the winglets being that it would effectively increase the aspect ratio of the wing without increasing span; act as rudders; possibly be used to alter the lift distribution along the wing; and lastly reduce the effective height of the wing at the tips, thereby increasing ground-effect. The usefulness of this device was to be tested in the wind-tunnel.

### Control surfaces

As the torsional stiffness of the inflatable wing is high, wing warping as a means of control was not considered and conventional elevons were adopted. The method of producing a trailing edge was similar to that of the "Reluctant Phoenix" which gave an excellent profile. (Fig 8) However, in order to allow up and down movement of control surfaces the two stretched skins holding the trailing edge struts had to vary in width. Fig.9 shows the arrangement which worked satisfactorily.

### Control Activating

Although polyester-film is dimensionally stable, calculations showed that the wing would stretch up to 9" when inflated, making conventional controls by cables or pushrods difficult or even impossible. The decision was taken to use an electrical system with all the control surfaces operated by model aircraft servos. The advantages of this system are that the travel and mixing of the elevons can be altered electronically. Also, by introducing a radio control the aircraft could be 'flown' from the ground by an 'expert', whilst an inexperienced but strong cyclist could pedal the aircraft into the air. Three servos were used in

each control surface along the wing and one at each winglet.

### Construction

The wing was constructed in a room approximately 12' x 26'. A working table 4' x 23' x 3'6" high with two lower troughs was built for this purpose. After marking all lines to be glued the polyester-film was placed into one of the troughs and fed over the worktop to be worked on. The assembled material was then lowered into the remaining trough in

### Bonding Process

The adhesive used throughout was a Bostik 1755 contact adhesive formulated specially for bonding polyester-film. To keep glue weight to a minimum, the minimum thickness of glue required for a secure bond was established and adhered to. A method was adopted which gave very consistent results.

### Application of adhesive to the polyester film

The polyester film is first spread over the worktop with a rubbing movement. The static produced by the rubbing process ensures that it sticks onto the worktop

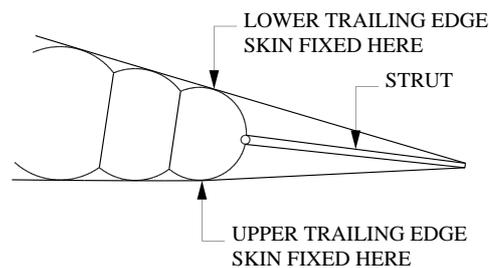


Fig 8.

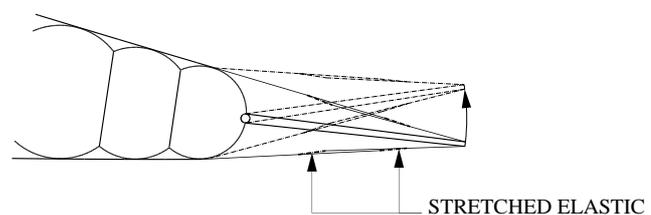


Fig 9.

smoothly. Masking tape is then applied on the area to be glued. Lastly, the adhesive is brushed on and spread with a spatula supported by the masking tape. The masking tape is then taken off, leaving a very uniform glue thickness. The glue thickness can be varied by using different thicknesses of tape or by building up several layers of tape. A similar method is used for the application of adhesive to the nylon fabric "T" tape, the tape being stretched over a smooth working surface.

### Wind-tunnel tests

Due to the demand for the 4ft x 4ft moving floor wind-tunnel at Imperial College, London, the wing was already six months into construction before the wind-tunnel became available. A Wortman reflex aerofoil of 15% thickness developed for gliders was selected for "Phoenix". This section has a relatively flat underside and avoids having any external concave curves. As a 20% thickness aerofoil was required, this section was enlarged to 20%. An exact profiled 19in chord test section. With all "Flats" reproduced, was tested. Tests at Reynolds numbers of 1.2 million (appropriate for "Phoenix") gave extremely disappointing results. Profile drag coefficient at  $c_l = .8$  was .057, rising to .085 at  $c_l = 1.0$ . An oil-smear test revealed that there was flow separation close to the leading edge with reattachment at .42 chord. It was assumed that the "Flats" in the profile were responsible for this defect. The other test carried out in this moving floor wind-tunnel was on a 28in smooth profiled wing with and without the designed drop-winglets, in and out of ground-effect. Three winglet shapes with symmetrical sections were tried at different angles to the airflow. At a height of .39 span above the floor the induced drag was 22% lower with winglets on. At .135 span height this reduction increased to 27%. No increase in profile drag was observed. The maximum reductions were obtained with the winglets set at  $0^\circ$  to the direction of airflow.

### Conclusion of wind-tunnel tests

As the wing was almost completed by the time of the wind-tunnel tests, a method to be found to prevent separation

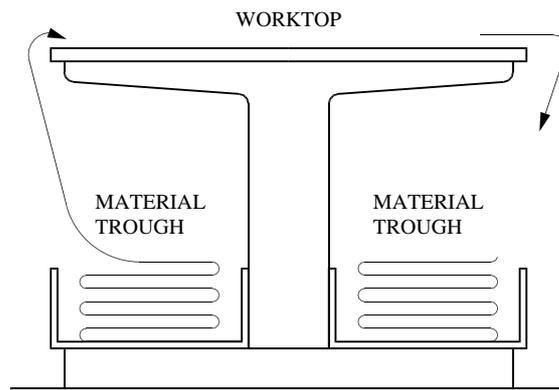


Fig 10.

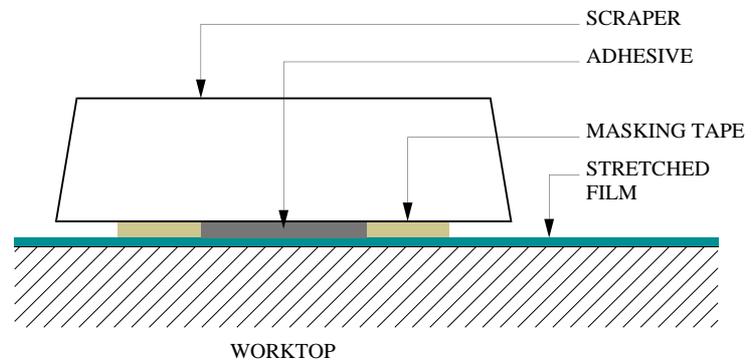


Fig 11.

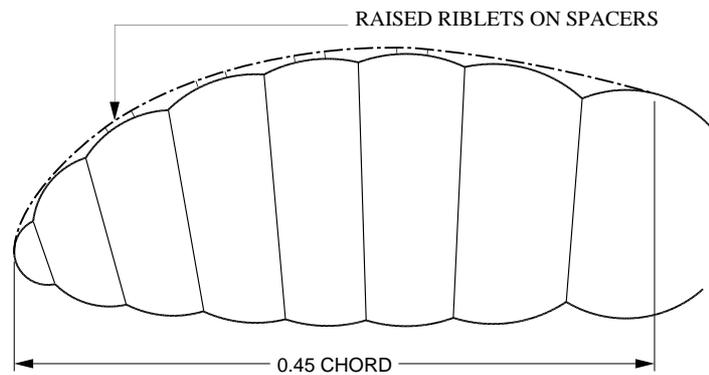


Fig 12.

of flow on "Phoenix's" wing. Frank Irving of Imperial College suggested that a series of flexible raised hoops or riblets be applied at intervals chordwise over the envelope and under the stretched aerodynamic skin in the hope that this would result in a much more uniform curve from the leading edge to beyond transition point. The solution was tested in a half size model of the inflatable envelope and showed that an excellent curve could be obtained. (Fig 12)

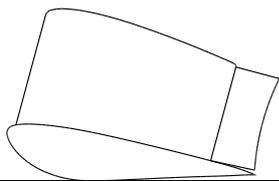
### Inflation tests

First inflation of the completed wing took place in a sports centre in Hampshire. Inflation took 20 minutes and the wing passed this test well. However deflation took over two hours as when suction was applied to the wind the webs closed up preventing the exit of air. After this first session two ports were made at

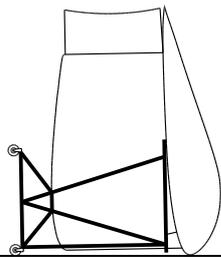
each winatip and subsequent deflations took 30 minutes During the first inflation the whole aircraft was rigged successfully. The application of the 6 microns aerodynamic skin proved to be the stumbling block. Due to its immense area of 3,200sq ft and the difficulty of booking the sports centre for more than a few hours at a time, it was months before it was finally attached smoothly over the envelope.

**Towed tests**

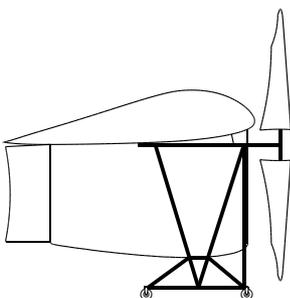
The power source used for the towed tests was a running man who held on to a nylon string attached to the aircraft. By the ease with which the aircraft took to the air we felt confident that the flow separation problem had been solved. The towed tests were conducted in a grass sports ground at Chiswick in London.



(1) INFLATION



(2) FRAME ON



(3) PROP ON

Fig 13

During the towed tests the aircraft crashed at least once from a height of over 20ft due to a wrongly connected aileron servo. The aircraft hit the ground, bending the wing which bounced without receiving any damage. By this time the aircraft proved fairly easy to move around the country on top of a 10ft long car roof-rack attached to a 1.3 litre engine European car. The wing had also seen over two dozen inflations.

**Rigging**

Due to the size of the wing, the following method for rigging was adopted (Fig 13):

- (i) The wing is inflated in the inverted position.
- (ii) The wing is then turned on to its leading edge for attachment of the pilot support structure and bracing wires.
- (iii) The aircraft is righted on to its wheels for attachment of the propeller.

**Man-powered flights**

Delays due to chain drive malfunctioning held up further tests in 1981. Early in 1982 permission was obtained from the London Docklands Corporation to test fly the aircraft inside one of their 600ft long empty warehouses. On 28th March



Phoenix at London Docklands March 1982.



First successful flight at London Docklands.

1982 the aircraft was rigged inside the warehouse. However, as weather conditions were ideal, Ian Parker, pilot and flight manager, decided to test "Phoenix" outdoors in the adjacent concreted lorry-park. After a long period of acceleration the aircraft took off under the power of Ian Parker. Further flights were made that day, all of about 20 seconds duration. It was observed then that there was adequate control in all three axes. Due to the extra weight of the plywood ribs and repairs. The weight of "Phoenix" had crept up to 1051b. The calculated mass of air held within the inflatable wing is 2001b, which explains the unusually long time taken for acceleration. In May 1982 "Phoenix" was handed over to Barry Jacobson, a member of the team, who was willing to take over development of the aircraft. Two production prototype inflatable aircraft are now being completed. One in polyester-film and the other in polyurethane coated Nylon fabric.

### Conclusions

"Phoenix" has proved that an inflatable man-powered aircraft can be made, can be easily stored and transported, and that such an aircraft can be built to withstand punishment.

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Phoenix packed on top of car with the team.