THE OPTIMISED MAN POWERED AIRCRAFT

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1 INTRODUCTION

The design of man powered aircraft has always been a pioneering venture, and even now it is in the same stage of development as engine powered aircraft were in the first decade of this century. Flight can usually be guaranteed, but performance cannot. Every new design that is built provides a real contribution to the total knowledge on the subject, and every mistake that is made increases the chances of success in a future design. To use this knowledge is not easy because it must be tempered by personal judgement and related to theoretical and practical considerations.

The Author's background is useful because it provides a reasonable basis for reaching the required compromise, having been involved in theoretical studies in man powered aircraft designs at University, the reconstruction of the man powered aircraft Mercury at Cranwell, and with the operation of Jupiter as one of the pilots.

2 CRITICAL ANALYSIS OF EXISTING DESIGNS

2.1 THE DESIGNS

To learn from other people's experience is, of necessity, to be critical. On available evidence, the weaker points of past and existing Kremer Prize designs are as follows:

a.	SUMPAC	This aircraft could have been built lighter. The pylon design was initially bluff, causing the propeller to operate in rough air. The wing had a large amount of twist, which, although giving elliptical lift distribution, did so at the expense of profile drag. Its directional control was poor.
b.	PUFFIN 1	This had a complex, if efficient, structure, but suffered surface buckling on the wing.
c.	PUFFIN 2	This, like Puffin 1 had a complex structure coupled with a new wing of greater span, which resulted in control difficulties.
d.	WEYBRIDGE/CRANWELL MERCURY	This aircraft is burdened by a massive wing. In limited tests, adverse effects of roll control in yaw are more powerful than the roll effects. The structure is complex and easily broken. The other defects are due to a 50 lb weight growth.
e.	CRANWELL JUPITER	This aircraft's glider - like construction is too heavy, but even with this burden, it is the most successful man powered aircraft flying.

f.	TOUCAN	Little is known about this aircraft's capabilities, but one would expect its massive span to result in rollover problems, due to the low forward speed and large difference in wing tip speeds during a turn. It has unconventional controls, with no rudder.
g.	LINNET SERIES	Information is lacking here, but the aircraft seem incapable of the kind of performance that one might expect considering their clean design and low structural weight. Their aspect ratios are, however low.
h.	HUREL AVIETTE	Information is again limited, but the aircraft is not a clean design, and with a span of 132 ft (40.23 m) must encounter serious roll-over problems. The structure is frail.

2.2 SUMMARY OF PRACTICAL INFORMATION

The most successful Aircraft have been those with small span. The theoretically higher power required is offset by less aeroelastic distortion, cleaner aerodynamics, and conventional controllability. In general terms, if wing span is greater than that of Puffin 2, (93 ft 28.35m), then control difficulties are present in some form. If wing span is allowed to drop below that of the Linnet series (73 ft, 22.25 m), the increased power required will give a disappointing performance. This gives a range of spans where a reasonable compromise between controllability and low power exists. It may be unfair to dismiss larger spans as impractical; they have, after all, flown in the forms of Toucan, Aviette and Mercury. The only one that the Author has worked with, however, has had disappointing performance and handling characteristics. The fact remains that the best aircraft from the practical point of view were the early ones, SUMPAC, Puffin and Jupiter.

Another drawback of large aircraft is the immense design and construction time required; over 10,000 hours in the case of Mercury. This means that the project is very protracted, lasting for years, and the workmanship can get poor as people lose interest. A smaller aircraft is quicker and simpler to build. These are great practical advantages.

3. DRAGONFLY DESIGN PHILOSOPHY

3.1 GENERAL

The preceding practical considerations must alsobe seen in the light of the theoretical side in order to contribute anything new to the state of the art. So far no mention has been made of the Kremer Prize course. The early aircraft were incapable of flying it, and yet it is being advocated that these aircraft were on the right lines.

Existing man powered aircraft were designed to be flown in ground effect, so reducing power required. It was initially thought that the figure of eight course could be flown at around 10 ft (3 m), but this involves so little margin for error that it is practically impossible.

With aircraft optimised to fly in ground effect, climbing to a reasonable height is equally impossible, because of the chaining effect of having to fly close to the ground in order to fly at all. If the aircraft is optimised to fly outside ground effect, then provided that the power required is not excessive, a positive rate of climb is implied, so that the aircraft can climb to a safe height to manoeuvre. It can then do a powered glide around the rest of the course. This enables the pilot to concentrate on flying at crucial stages of the flight without having to maintain a high pedalling rate.

The other design features desirable are that the aircraft should be as simple as possible to design and build, and that it should be completely conventional and involve as little gimmickry as possible.

3.2 OPTIMISATION OF LAYOUT

The power required for flight is:-

$$HP = \frac{0.0527}{\eta_p \eta_t} \frac{D}{q} \left(\frac{W/S}{C_L}\right)^{3/2}$$

HP = Horsepower required at pedals

D = Drag (lb)

q = Dynamic Pressure (psf)

W = Weight (lb)

S = Wing Area (sq ft)

C_L = Lift Coefficient

η_p = Propulsive Efficiency

η_t= Transmission Efficiency

In order to optimise this, it is necessary to know how the weight and drag vary with wing area and span for different layouts.

Considering the weight first, an analysis of the empty weights of existing aircraft will give an empirical formula for weight as a function of wing area and span. The function that was found to hold for a single seat aircraft was:

$W = 25 + 0.158\ S + 0.052.b^{3/2}$ + pilot weight

where b = span

This gives an accuracy of -5% +4% which can be accounted for by different structural techniques.

Dealing with drag, it is convenient to standardise all the layouts by using the same wing section.

This is partly invalid, because a low aspect ratio aircraft could use a thinner section, but in general they do not. It is essential to include the variation of wing drag coefficient with Reynolds Number. The section chosen was the Wortmann FX 63137, and all the wings were assumed to have elliptical planform. The induced drag coefficient was held constant at 1.1 to cater for aeroelastic distortion. The aircraft were assumed to be operating out of ground effect. The parasite drag coefficient was taken as 0.006.

The optimisation was carried out at lift coefficient of 1.0 and 1.1 with pilot weights of 140 lb and 154 lb. Span was varied from 70 to 100 ft in the divisions 70, 80, 90, and 100 ft (21.3, 24.4, 27.4, 30.5 m). The axes were horsepower at the pedals and aspect ratio. The most promising graph was the one of lift coefficient 1.1 and pilot weight 140 lb (fig.1).

3.3 RESULTS OF OPTIMISATION

1. The power required for spans of 80, 90, and 100 ft were similar. Only 70 ft span had a large power requirement.
2. The optimum aspect ratio is 35 or larger.

The advantages of a small span are numerous, and in view of the small gains in using greater spans, a span of 80 ft was selected. The aspect ratio of 35 was thought to be too high to cater for unforeseen weight increases, so a value of 30 was chosen. The resulting wing area was 213.5 sq ft (19.83 sq m), and the empty weight expected was 96 lb. The calculated power required at the pedals was 0.44 HP to maintain straight and level flight out of ground effect with a 140 lb pilot.

4. THE AIRCRAFT

4.1 GENERAL (fig.2)

In the interests of a simple design, it was decided that the aircraft would be of a strictly conventional layout. Unconventional layouts and features have not been proved to be superior, and most have serious shortcomings. It was decided to base the layout on the well proven lines of Jupiter, with a few modifications.

4.2 THE WING

The wing is of elliptical planform with no twist. It is usual, when estimating the drag of a wing, to assume a mean drag coefficient equal to that of the mean chord. If a straight tapered wing is considered, and a Schrenk approximation carried out, it will be found that a large part of the wing is operating at a higher lift coefficient than that designed for. This increases the drag coefficient considerably if the design lift coefficient is already high. Also, those parts of the wing operating at higher incidence tend to have smaller Reynolds Numbers and even higher drag. The net resultis that the wing profile drag can be 10 to 15% higher than expected. Curiously, for an elliptical wing the net profile drag is about 7% lower due to the uniform local incidence and generally higher Reynolds Numbers outboard.

4.3 ACCOMMODATION AND PROPULSION

The pilot sits beneath the main spar in a conventional seated position, with pedals placed in the aircraft's nose. There is no evidence to suggest that cycling position has any influence on power produced, and a seated arrangement produces a better nose profile with less of a fin effect. Drive is by a chain via a road wheel to the propeller mounted on a pylon above the wing. The propeller diameter is 9 ft (4.08 m), and its expected efficiency is 89%. The road wheel is driven to facilitate ground handling.

4.4 CONTROLS

The controls are conventional with ailerons, rudder and all moving tailplane. The aircraft has fin and tail volumes similar to those of Jupiter, which is an aircraft that has displayed few control difficulties. The pilot's controls are in the form of a handlebar mounted from the cockpit floor, set ahead of his knees.

5.STRUCTURE

5.1 THE WING (see fig.3)

The 2.2g main spar is a simple box of spruce and plywood internally reinforced with balsa gussets. The wing ribs are cut from a sandwich of 1/32" balsa - 0.3" Expanded Polystyrene Foam - 1/32" balsa. This is a very light and simple method for making ribs. Ribs are placed every 12" (30.5 cm) with riblets in between. The total rib weight is 3.5 lb (1.6 kg). The leading edge is covered with 1/16" balsa to the rear of the spar. This provides the torsion box. This kind of construction is only suitable for small high aspect ratio wings.

The wing is wire braced at points 15 ft (4.57 m) either side of the centreline. This reduces the spar weight by 15 lb (6.8 kg), for a small drag penalty. The wing section originally specified was 20% thick. Curiously, the wing weight calculated was about the same as for the present thin wing. This was due to the increased weight of the spar webs and the wing ribs, offsetting the reduced flange weight.

5.2THE FUSELAGE

The fuselage is made largely of L section aluminium alloy riveted together with joining plates. The fuselage boom is triangular in section to reduce weight, and has three aluminium longerons cross braced with balsa, epoxied in position. The fuselage pod is made up of balsa and thin expanded polystyrene foam sheet. The complete aircraft is covered in Melinex type 377.

5.3 WEIGHT

After a careful weight analysis, the calculated empty weight was found to be 92.5 lb (41.96 kg). Of this, 15.3 lb (6.94 kg) is glue. In view of the amount of metal in the aircraft, this was thought to be reasonable.

6. PERFORMANCE AND CONTROL

6.1 POWER REQUIRED

Fig 4 shows a graph of power required at the pedals against height for the aircraft with a 140 lb pilot. The product of the propulsive and transmission efficiencies was taken as 80%

At all heights, power required is considerably less than power available, which is assumed to be 0.5 HP. This figure has been shown to be easily maintainable.

6.2 CLIMB

Assuming a power input of 0.5 HP for 5 minutes, the climb performance and ceiling can be calculated. These are shown in Fig.5. The take-off will take about 25 secs, so this leaves 4 mins 35 secs to climb. In this time, a 140 lb pilot will be able to reach 62 ft (18.9 m), and a 154 lb pilot will reach 46 ft (14 m). Both are safe heights to start flying a figure of eight course. The distance covered in climbing to 62 ft is 6,000 ft (1830 m). Fortunately, runway 13 at Prestwick drops 30 ft (9.1 m) over this length, so we can add this to our height, giving the aircraft a ceiling of about 90 ft (27.4 m) in the most favourable conditions.

6.3 CONTROL

A slow moving aircraft with a small yaw rate suffers from a great difference in the local airspeed over each wing. The resulting rolling moment is into the turn, and must be held off with aileron. To add to this problem, the faster wing now has up aileron and the slower wing has down aileron. If the lift is summed over the span, it will be discovered that there is a net loss of lift which requires the aircraft to fly at higher incidence (table 1).

Table 1.

Speed= 28 ft/sec, $C_L = 1.15$

Bank Angle (degs)	Aileron Defection req'd (degs)	Lift Loss (lb)
3	2.5	2.5
5	4.1	5.2
10	7.7	18.3
15	9.8	32

This effect is aggravated by:

1. Reducing airspeed (at 24 ft/sec, the deflection and lift loss double)

2. Increasing span

3. Decreasing wing loading

This implies that any large span aircraft with a low wing loading will have these problems in a serious way unless bank angles are limited to 1 to 2 degrees. It can be seen that a bank angle of 5 degrees is reasonable at 28 ft/sec. This gives a radius of turn of 280 ft (85.3 m). To maintain controllability, it is essential to maintain speed. This will be done by flying at constant attitude by the use of a mercury switch attitude indicator as pioneered on Jupiter.

6.4 THE KREMER COURSE

The course as envisaged (fig 6) has been assumed to involve a climb to 62 ft and neglects the 30 ft runway drop at Prestwick. It consists of:-

1. Take-off and climb for 5 mins at 0.5 HP

2. 0.25 HP powered glide around the first turning point, downwind, and around the second turning point.

3. Zero power glide to the finish.

At all points, the heights are safe, and the total energy used is 108 760 ft-lb. If necessary, the maximum height can be lowered to 30 ft. This would involve flying the course level, and would have much less margin for error, but would only require 75 100 ft-lb of energy.

7.CONCLUSION

The aircraft described here is intended to be an all round improvement over older designs and, on paper at least, should be able to fly the Kremer course with little difficulty. This appears to be achievable by an aircraft that is completely conventional, simple to build, and which has no gimmicks. It has been pointed out that the only original design feature of this aircraft is that it has no original design features. Its performance has been looked at pessimistically, and the aircraft still operates nowhere near its critical limits. These were the aims set at the beginning of the project.

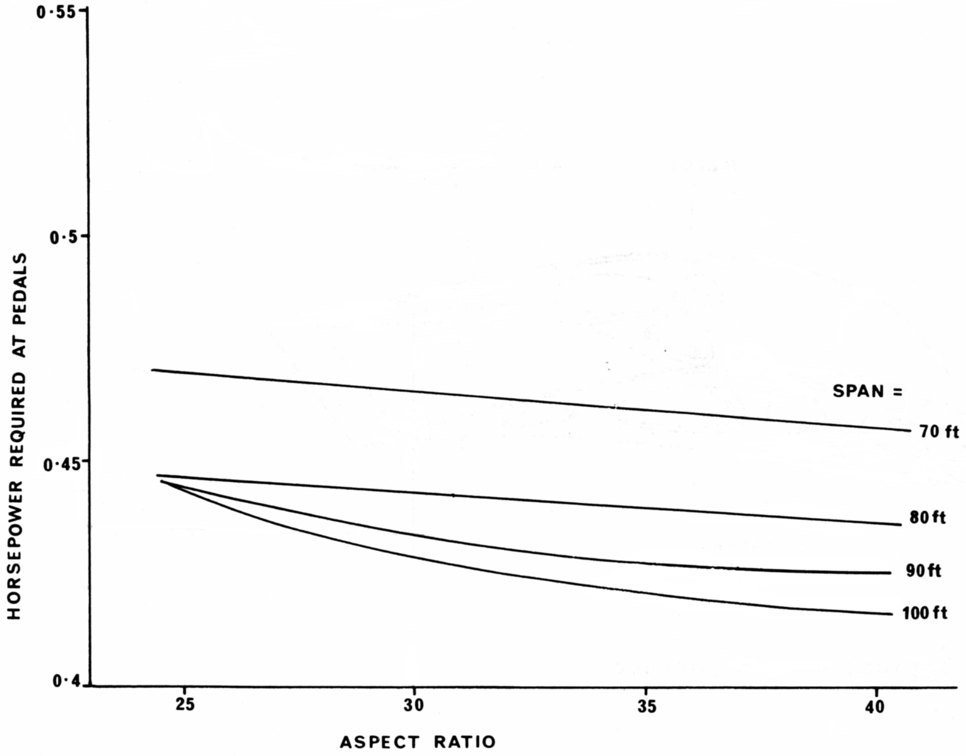

Fig. 1. Layout Optimisation for $C_L = 1.1$, 140 lb pilot.

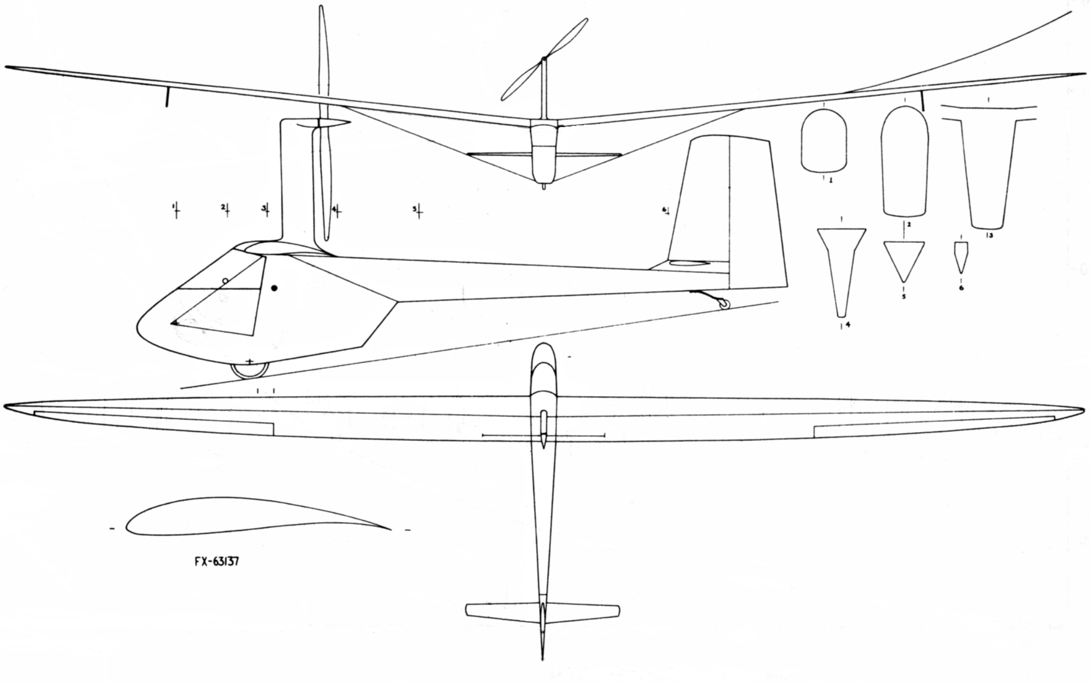

Fig. 2. Dragonfly General Arrangement

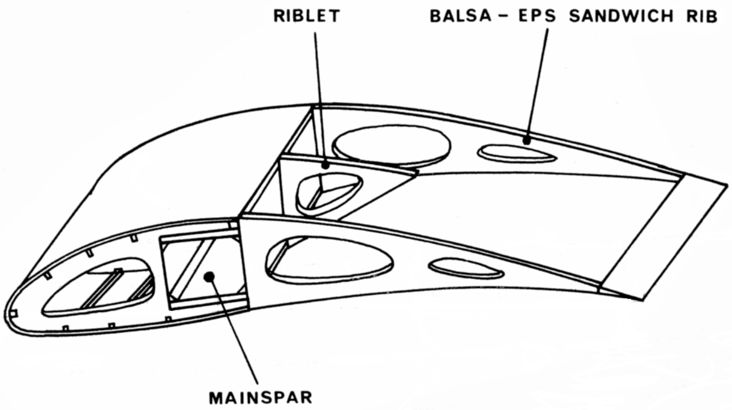

Fig. 3. Typical Wing Structure

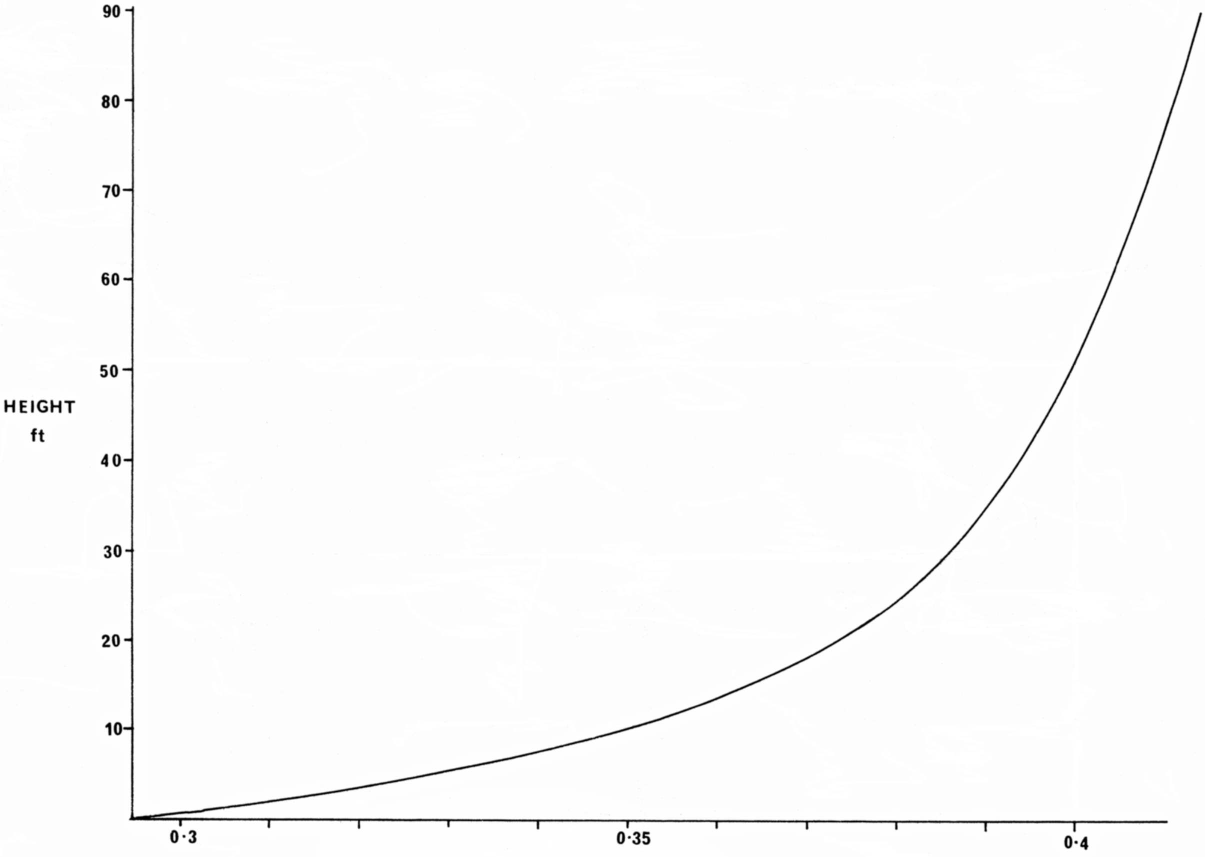

Fig. 4. Power required at pedals with height, 140 lb pilot

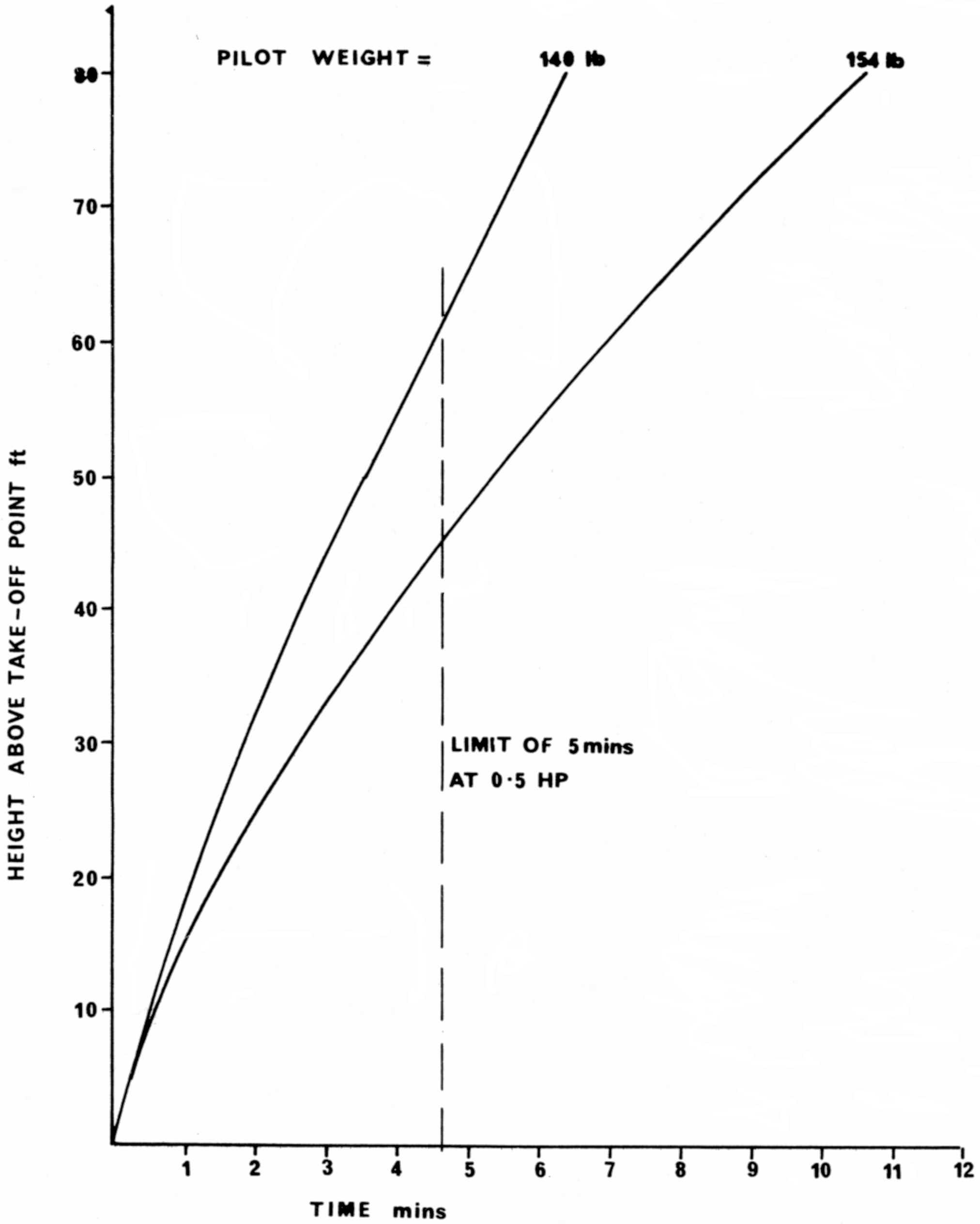

Fig. 5. Time to height.

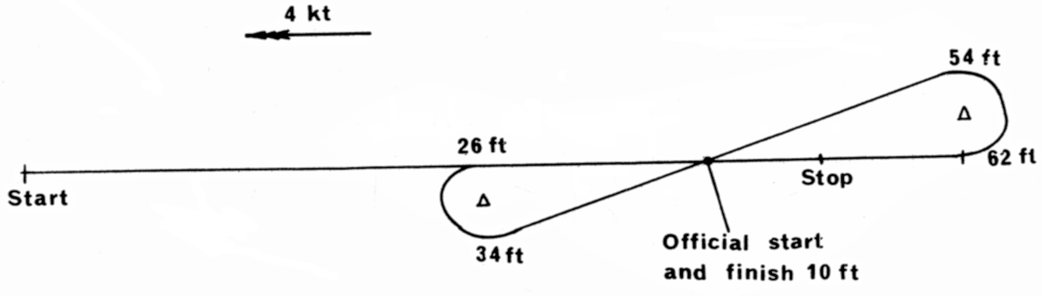

Fig. 6. The Kremer course.