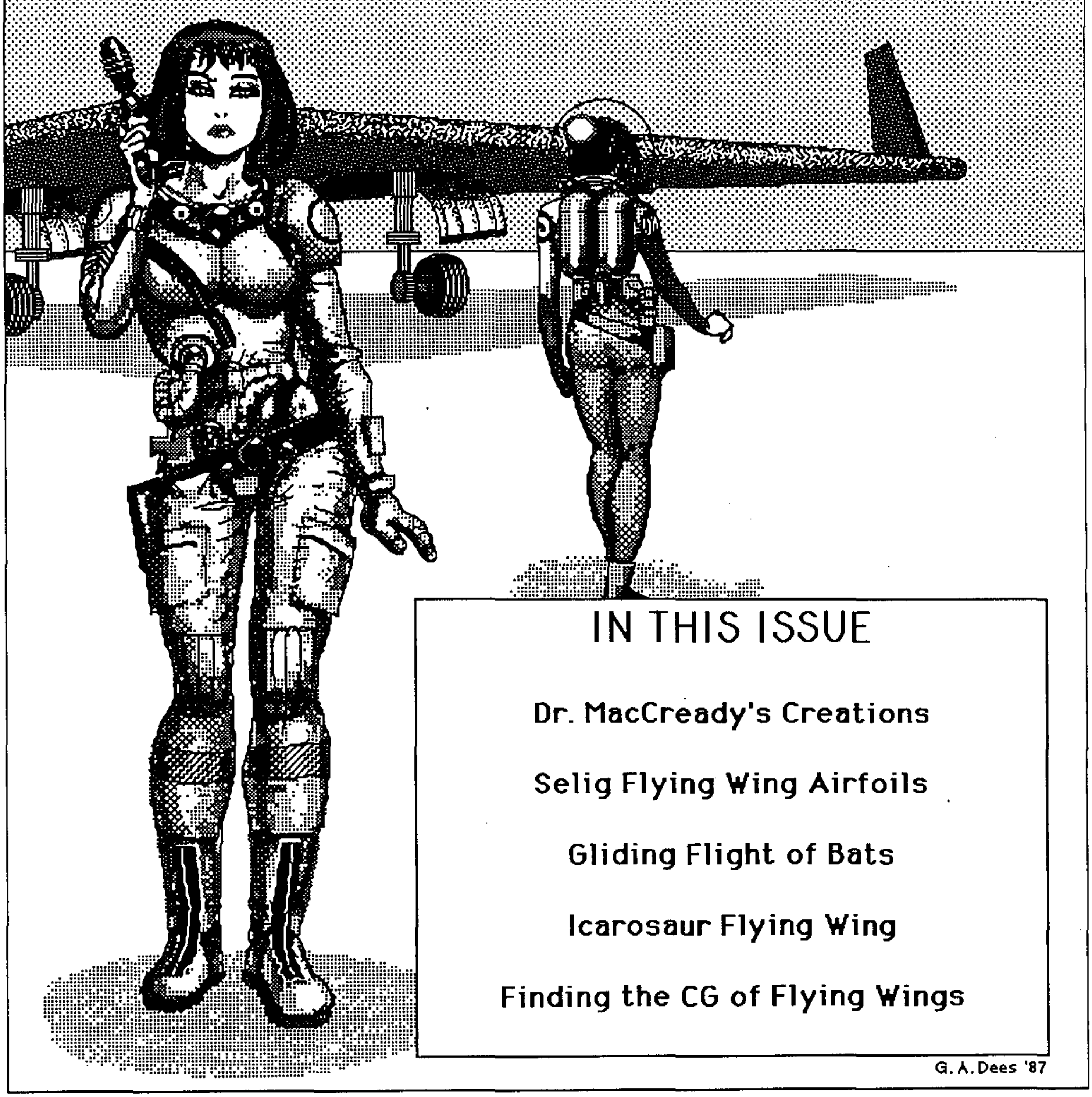
SOAR TECH # 7
The FLYING WING Edition



IN THIS ISSUE

G.A. Dees '87

SOARTECH VII JUNE 1987

This is my first effort at producing an entire issue of Soar Tech and I hope that it won't be the "issue that killed a good thing". My thought processes are quite a bit different from Herk Stokely's and thus, you will find at least one article in this issue that you might not think belongs. I hope to illuminate . . . .

You may wonder why a paper on bats appears in a journal devoted to R/C sailplanes. Well, one of my degrees is in zoology and I used to spend a lot of time reading about and observing bats in the past. As a result, there is an awful lot of "bat" aerodynamics included intuitively in the reasons for my choice of an undercambered airfoil for the center "bat-tail" section and reflexed tip sections of my "Icarosaur" flying wing design. Long after the completion of "Icarosaur", I came across Pennycuick's paper on bat gliding and found the documented connection between the bat and flying wings.

I was, indeed, fortunate to have Dr. Paul MacCready and Dr. Alec Brooks of Aerovironment, Inc. as contributers for this issue. Last year, Dr. MacCready's pteradactyl ornithopter project captured my imagination. It took a bit of detective work to find him and, with a "bribe" of previous issues of Soar Tech, a copy of "Icarosaur" plans and a video tape of it in flight, I was able to secure two papers for use in this issue. I also was able to acquire press passes for the flight of the pteradactyl at Andrews Air Force Base last May. Drs. MacCready and Brooks will also receive copies of this issue. Like the bat paper, papers concerning the "Gossamer Condor", "Gossamer Albatros", and the pteradactyl ornithopter do not deal with R/C sailplanes directly. However, I feel that much of the technology applys to flying wings in general and when I asked Dr. MacCready whether or not he considered his creations flying wings, he said: "Well, they don't have tails . . . so, I guess they are!" Dr. MacCready's team also has a large percentage of R/C sailplane enthusiasts as members.

Soar Tech VIII will consist entirely of the results of Micheal Selig's wind tunnel research on R/C sailplane airfoils. Micheal's work should be completed this summer and as soon as possible afterwards, Herk will release it in issue number 8. **You may order it now** by sending $5.00 (within the U.S. and Canada) or $8.00(US) for overseas to: H. A. Stokely, 1504 Horseshoe Circle, Virginia Beach, VA 23451 USA.

Also of interest to the Flying Wing Freaks out there is the fact that, while accumulating material for Soar Tech VII, I found more than I needed, thus, assuring enough for another Flying Wing Issue at a later date. Amongst these papers are several by A. R. Wyel that are cited as references in Pennycuick's bat paper. These, it turns out, are excellent references on flying wings.

" He was so damned disgusted with the Flying Wing that he tried to stop the firemen from putting out the flames."

---- the actions of test pilot
Russ Schleeh as recounted
by Chuck Yeager
in his book, *Yeager* .

SOARTECH JOURNAL

"SoarTech", began in 1978 as a series of technical papers in the Tidewater Model Soaring Society newsletter which we called the TMSS Technical Journal. With encouragement and ideas from Jim Gray and Bruce Abell, it began to be published by TMSS as the "SoarTech" Journal. It is an English language technical forum for Radio Control Soaring; containing papers submitted by interested modelers, and from other publications. It's intended to provide a vehicle for the publication of information and data which is too lengthy or too technical for publication in the popular press.

It is now edited, published and distributed by H. A. (Herk) Stokely, 1504 North Horseshoe Circle, Virginia Beach VA 23451 Phone (804) 428-8064. The mission and purpose of SoarTech is to make available to RC Soaring enthusiasts (and others), technical information and data that may not be available from other sources.

PAPERS INCLUDED IN THE SEVENTH ISSUE

Performance Analysis of the Horten IV Flying Wing

By DEZSÖ GYÖRGYFALVY, Aerophysics Department, Mississippi State University

Presented at the 8th OSTIV Congress, Cologne, Germany, June 1960

Introduction

It has been recognized from the beginning of the development of the sailplane that the key to performance improvement was in drag reduction. It has been also known that the total drag consisted of three major components: induced, profile, and parasite drag. The development started first in reducing the parasite drag by elimination of struts, wires, open cockpit, etc. Then, it continued in decreasing the induced drag by using high aspect ratio. The third stage of the development is going on at the present time, when the major effort is concentrated on lowering the profile or friction drag, since the possibilities of induced and parasite drag reduction are nearly exhausted.

During the second stage of development, the continuous efforts for lower and lower drag led to the idea of the flying wing design. This offered the complete elimination of the parasite drag in addition to lighter weight and lower cost. But, at the same time, numerous problems of stability and control were to be overcome. These difficulties discouraged most of the designers, but the Horten brothers took up the problem with great determination and basically solved it. It is most remarkable that the fourth of their models, the Horten IV, was already better, or at least equivalent in performance to those of conventional design, which were developed with all the experience gained through dozens of previous models. This successful development, however, was interrupted by the war, and the last two models of the line, the Horten IVb and Horten VI, remained unevaluated.

Since the war, the emphasis in sailplane development has been concentrated mostly on the profile or friction drag reduction of conventional types. The adoption of laminar airfoils and new technology brought significant progress, and the seemingly ultimate gliding ratio of 40 to 1 has been reached. But, in this state of development when the greatest effort is necessary to eliminate one or two thousandths from the profile drag coefficient, the presence of the parasite drag due to the fuselage and tail becomes more and more annoying, and the idea of the flying wing configuration comes into prominence again.

For this reason, as a part of the sailplane research program conducted by the Aerophysics Department of Mississippi State University, an investigation was projected into flying wing sailplanes, and a Horten IV was chosen for that purpose as the most advanced design of its class.

Preliminary performance measurements of the Horten IV were made by the DFS in comparison flight with the D-30 Cirrus in 1943, and reported by Hans Zacher [2].

It was pointed out that, although the Horten IV was one of the best performing sailplanes of that time, the actual performance was well below that expected.

The basic aim of our research was to find out why the estimated performance could not be achieved and whether or not the factors causing the lower performance are inherent in the flying wing design.

Preliminary flight tests at Mississippi State University showed even lower performance than reported by Zacher. Since the plane was not in good condition at that time, it was decided to overhaul it, improving the wing surfaces as much as possible and making some modifications on the center section, such as streamlined housing for the nose skid and improved canopy contour. Finally, the projected flight tests were conducted in the fall of 1959, and the results of the evaluation are presented here.

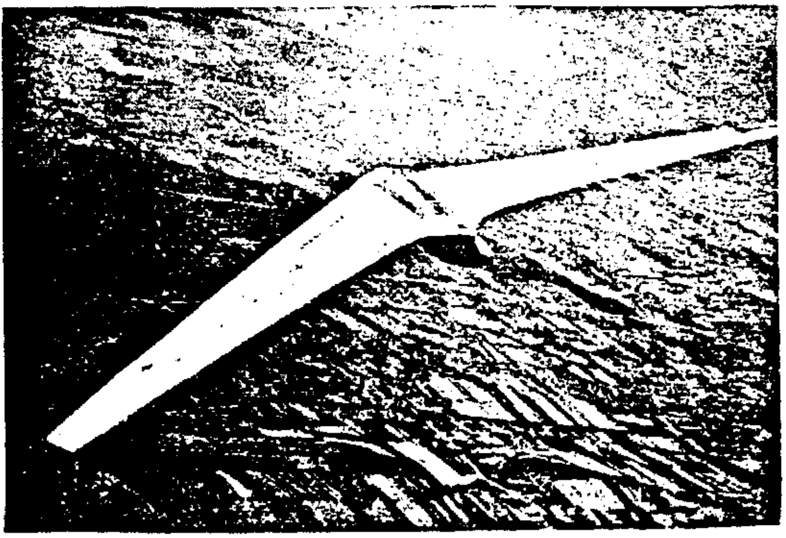
Results of Recent Performance Measurements

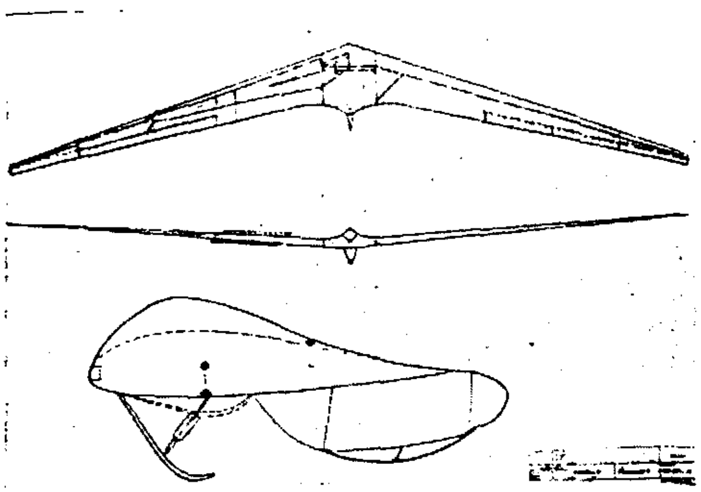
Figure 1 shows the performance curves. The test points of several flights are indicated by different symbols. The points were weighed according to the customary method [3], and those of full weight have solid symbols. In addition to our measurements, the former DFS test results are also indicated. They are adjusted to $W = 366$ kg, the gross weight of the recent tests.

The best gliding ratio of the Horten IV was expected to be 0.37. The flight tests, however, indicated considerably lower performance. Nevertheless, there are some differences between the flight test points. While the drag polars in Figure 2 almost coincide at low lift coefficients, the deviation between them becomes larger and larger as the lift coefficient increases. In other words, the slope of the linearized drag polar is steeper according to the DFS measurements, which means better span efficiency. It should be noted, however, that the span efficiency is affected by the C.G. position, and it is not given for the DFS test. If the C.G. was located considerably farther back in the DFS test, or if the two planes were not the same, the disagreement is understandable.

The most important performance and aerodynamic data are summarized in Table 1.

Three features of the aerodynamic characteristics are most remarkable.





(1.) The minimum drag coefficient, $C_{D_{\min}} = 0.0125$, is barely lower than that of a good conventional design of that time in spite of the elimination of the fuselage and tail. $C_{D_{\min}}$ was 0.0135 for the D-30 "Cirrus", and 0.015 for the DFS "Reiher" [4].

(2.) The drag rapidly increases with the lift coefficient, that is, the slope of the linearized drag polar is extremely shallow, which means poor span efficiency or low effective aspect ratio.

(3.) The maximum lift coefficient, $C_{L_{\max}} = 1.125$, is relatively low also.

Analysis of the Drag Components

The performance measurements represented only the first step in our investigation. As mentioned before, the basic aim was to find out the reasons for the unusual behavior and to make clear the interaction of the several influential factors. For this a detailed study of the individual drag components was necessary, or in other words, the drag polar was to be broken down into its elements.

The Profile Drag

The profile drag was measured at several places along the span by means of an integrating wake rake. The method is described in Reference 5. The measured profile drag polars, Figure 3, have the following features: Going outwards along the span, the drag increases considerably. This is partly due to the decrease of Reynolds number, but most likely is due to the lack of cleanliness of the airfoil caused by elevon surfaces, dive brakes, and drag rudders.

In the case of the innermost test section, the minimum profile drag coefficient $c_{d_{p\min}} = 0.009$. Then the drag gradually increases at the higher lift coefficients, and amounts to $c_{d_p} = 0.015$ at $C_L = 1.125$.

Although, in view of the present state of the art, an airfoil of such a high drag is considered very unfavorable, it was not worse than other contemporary airfoils [4, 6].

For the rest of the test sections, the airfoils are not clean due to dive brakes and control surfaces. At the second and third test section there is a rapid drag increase at high lift coefficients. This is generated by turbulent separation, which occurs on that part of the wing as an initiation of the stall.

For the fourth test section, the rate of drag increase with lift coefficient is much greater than for the inner sections, but there is no rapid growth in drag at high lift coefficients. This is because the center elevon has large negative deflection which results in higher drag at moderate lift coefficients, but does not allow separation at the high lift coefficients.

The outermost test section has approximately two and one-half times higher drag than the innermost one. Numerous factors, such as contour and surface imperfections, drag rudder, low Reynolds number, large control surface-chord ratio, etc., contribute to develop this extremely high drag at the wing tip. It is peculiar that the minimum drag occurs at $C_L = 0.4$, and below that the drag increases again. The probable reason for this is the discontinuity in profile contour which causes the flow to separate from the drag rudder when the elevon has zero or positive deflection, while the overhanging nose of the Frisetype elevon creates rapidly increasing drag at high lift coefficients when large negative deflection is applied.

Based on the sectional profile drag measurements, the spanwise profile drag distribution and resultant profile drag polar were determined. Figure 4 shows the local profile drag coefficients along the span. These curves, multiplied by the local chord length, represent the effective drag distribution and the resultant profile drag is calculated as:

$$C_{D_p} = \frac{2}{S}\int_0^{b/2} (cd_p\, c)\, dy$$

The results are given below.

Resultant Profile Drag Coefficients

C_L	0.2	0.4	0.6	0.8	1.0	1.05	1.125
C_{D_p}	0.0115	0.0120	0.0132	0.0151	0.0179	0.0208	0.0223

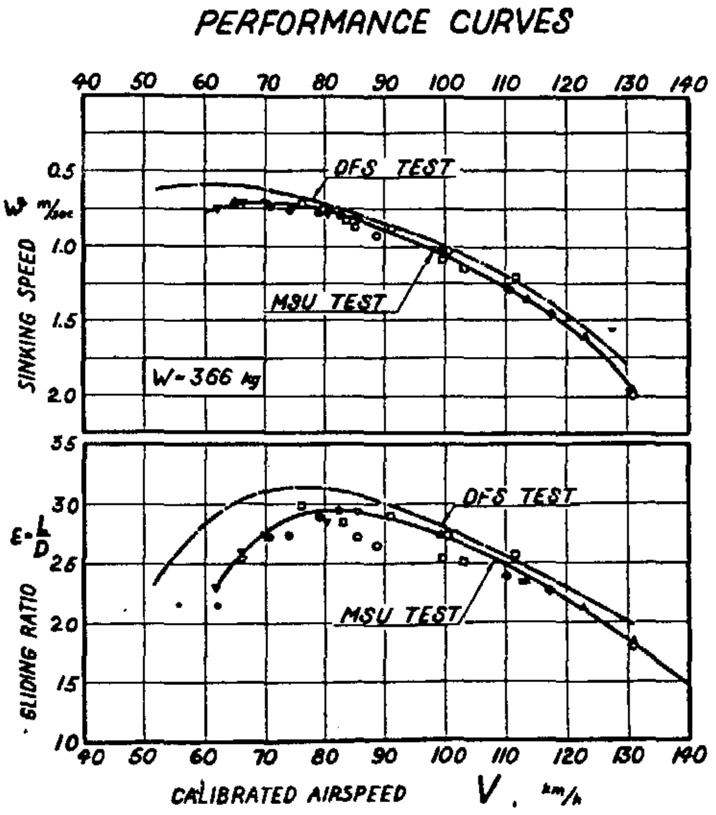


Fig. 1

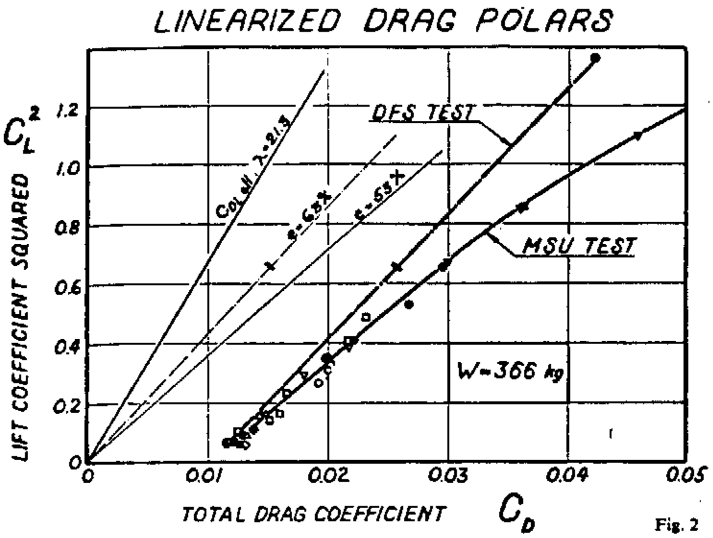


Fig. 2

Induced Drag

The induced drag coefficient is defined as:

$$C_{D_i} = \frac{C_L^2}{\pi \lambda} (1 + \delta)$$

where the factor δ represents the induced drag increment due to the deviation of spanwise lift distribution from elliptic, which would give the minimum induced drag. It is customary to express the induced drag coefficient also as:

$$C_{D_i} = \frac{C_L^2}{\pi \lambda_{\text{eff}}}$$

that is, to consider the induced drag increment as a consequence of decreased effective aspect ratio where

$$\lambda_{\text{eff}} = e \lambda$$

and e, the span efficiency, is defined as

$$e = \frac{C_{D_i \text{ell}}}{C_{D_i}} = \frac{1}{1 + \delta}$$

The low span efficiency of the Horten IV indicated that the induced drag increment might be very high because of the heavy twist and control deflection. Therefore, a detailed calculation was carried out concerning the spanwise lift distribution and actual induced drag.

The factor δ is determined by the spanwise lift distribution which is affected mainly by the taper, sweep, twist, and control deflection. The spanwise lift distribution was calculated according to O. Schrenk's approximate method, supplemented by Weissinger's correction for sweep [7, 8, 9].

The most unusual among the influencing factors considered is the control deflection. In low speed flight the center and outboard elevons are deflected up as much as 15 degrees, which results in a considerably decreased effective local angle of attack or lift coefficient.

The elevator deflection angles are shown as a function of the lift coefficient in Figure 5. This was obtained by collating the curves $\delta_E^* = f(C_L)$ and $\delta_E^\circ = f(\delta^*)$, where δ^* represents the displacement of the control grip and δ° is the control surface deflection in degrees.

According to theory, a small control deflection results in a change of effective angle of attack defined by the control power derivative

$$\frac{d\alpha}{d\delta_E}\text{, that is, } \Delta\alpha = \frac{d\alpha}{d\delta}\,\delta_E$$

This change in angle of attack due to control deflection was considered as additional twist, and the resultant lift distribution calculated accordingly.

Figure 6 illustrates the deviation of the lift distribution from the elliptic for the wing with basic twist only, and for that with control deflection included. Two examples are presented: $C_L = 1.00$, and $C_L = 0.25$. As can be seen, at high lift coefficient, the large negative control deflection greatly increases the deviation of the $(c_l c)$ curve from the elliptic, while the basic twist results in minor difference.

However, at low lift coefficient, the control deflection, being positive, decreases the effective twist and brings the resultant lift distribution closer to the elliptic than it is for the wing of basic twist.

The induced drag increment, δ, was calculated by the formula [Reference 10]:

$$1 + \delta = \frac{\sum_n (n a_n^2)}{a_1^2}$$

where a_1 and a_n are the Fourier coefficients of the $(c_l c)$ lift distribution curves.

The results are summarized in Figure 7, where δ is plotted versus C_L. The effect of taper, sweep, twist, and control deflection can be delineated clearly. The extreme taper causes an induced drag increment of about 2.5 per cent, as compared to an elliptical planform. The sweep, by shifting the load towards the tips, counteracts the taper and reduces δ to about 1.5 per cent. Contrary to the former two factors, in which cases δ is constant with the lift coefficient, the twist results in a rapidly increasing δ as the lift coefficient decreases. This is true because the basic load distribution due to twist remains unchanged, while the additional load distribution determined by the planform proportionally decreases with

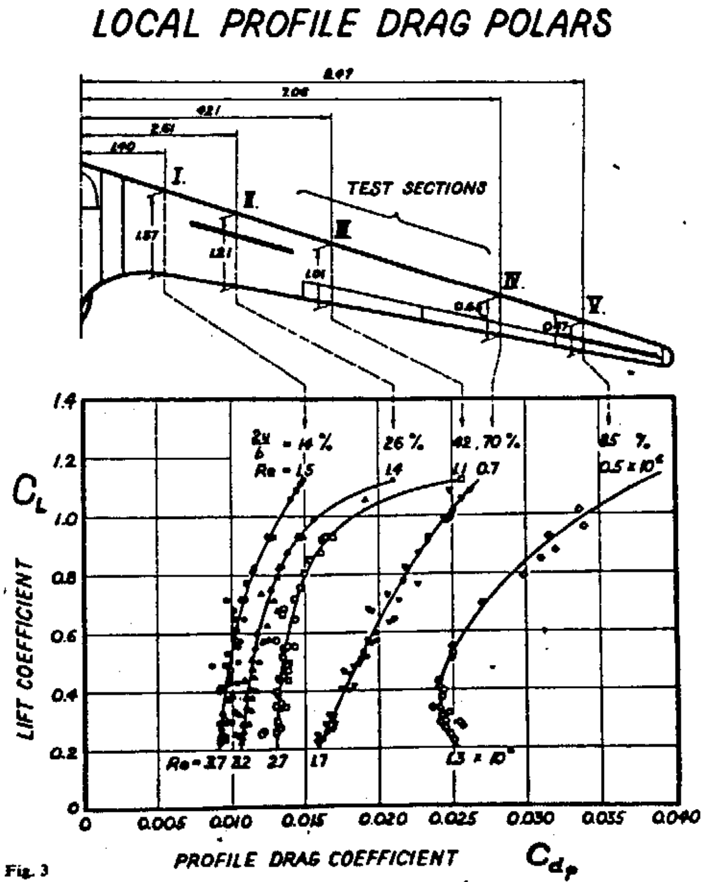


Fig. 3

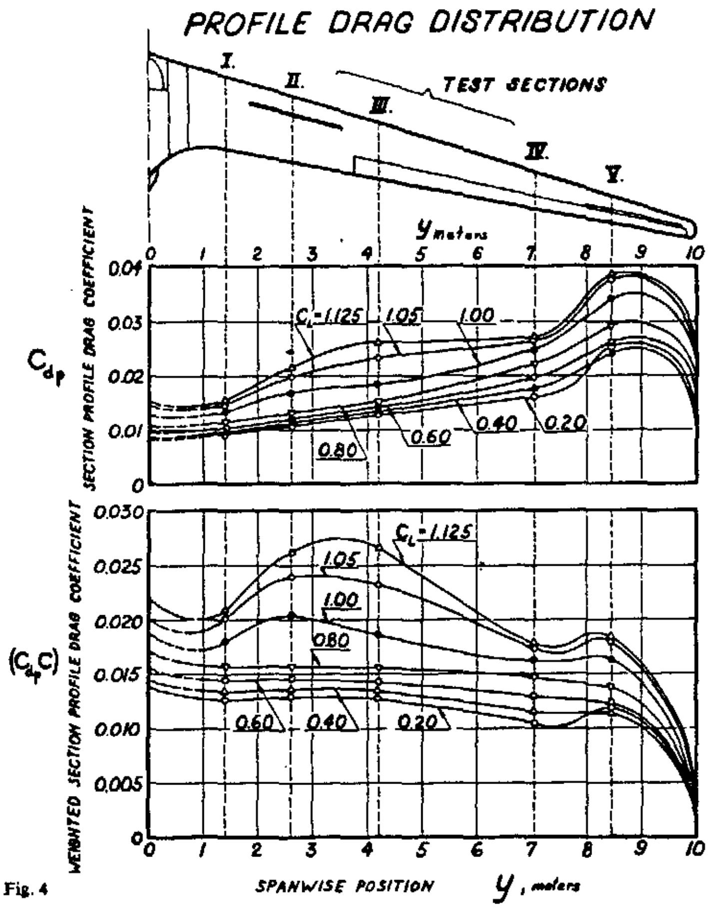


Fig. 4

the lift coefficient and, since the resultant load distribution is the sum of the two above, at low lift coefficients, the effects of the twist become more and more predominant. While $\delta = 2.5$ per cent at high lift coefficients, it has grown to $\delta = 59$ per cent at $C_L = 0.25$. The control deflection required to trim has an alleviating effect on the induced drag increment due to twist at the lower lift coefficients. The actual conditions are represented by the heavy curve which includes the effect of all influencing factors. By reference to this, it can be seen that $\delta = 35$ per cent at $C_{L\,\max}$ and gradually decreases to $\delta = 24$ per cent at $C_L = 0.5$. Below $C_L = 0.5$, δ increases again, but not nearly so rapidly as in the case of the twisted wing without control deflection.

Parasite Drag

The parasite drag of a flying wing is supposed to be negligible, since the frontal and wetted area of the fuselage are very small compared to the entire wing area. Tuft observations on the Horten IV, however, indicated intense separation on the rear part of the cockpit hatch which implies a source of considerable parasite drag. Figure 8 shows tuft photographs of the canopy at two typical speeds. As can be seen, the separated region diminishes as the speed increases. Figure 9 presents the extent of separation evaluated from tuft photographs. The attitude of the plane as well as the angle of flight path, pitch, and angle of attack are given also. The steep nose up attitude of the canopy at high lift coefficients, which incorporates severe adverse pressure gradients, is apparently the major source of the separation.

Since there is no practical method available for measuring the parasite drag numerically, it is determined indirectly by subtracting the profile and induced drag from the measured total drag. The remainder is considered parasite drag.

Breakdown of the Drag Polar

In Figure 10, the drag polar is divided into the major components discussed in the foregoing paragraphs. The induced drag consists of two parts: the theoretical value, that associated with an elliptic lift distribution; and the increment, due to the actual conditions. The former part being proportional to the square of the lift coefficient, appears in the linearized drag polar as a straight line with a slope determined by the geometric aspect ratio. At the maximum lift coefficient, this part amounts to about 35 per cent of the total drag. The other part, the induced drag increment, progressively increases with the lift coefficient, and at $C_L = 1.00$, results in about 30 per cent higher induced drag than the theoretical. Thus, the total induced drag amounts to about 46 per cent in low speed flight.

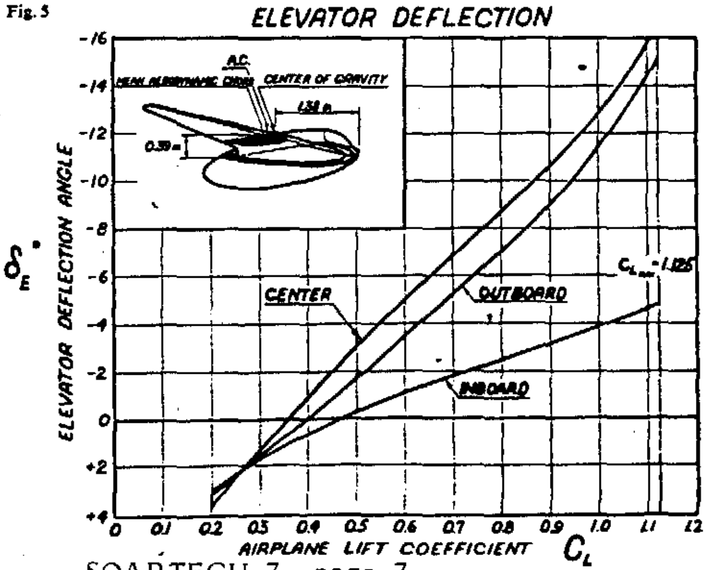
The parasite drag is negligible at low lift coefficients, but begins to grow gradually between $C_L = 0.4$, and 0.7. Above $C_L = 0.7$, the separation from the canopy expands rapidly and the parasite drag rises from 3 to 14 per cent of the total.

The profile drag forms a major part of the total drag throughout the entire speed range, and becomes more and more predominant at low lift coefficients. It is 90 per cent at $C_L = 0.2$. It can be seen that the main responsibility for the lower than expected performance rests with the high profile drag and its intense growth with lift coefficient.

On the basis of the Figure 10, the low span efficiency can be explained also. The span efficiency is defined as the ratio between the slopes of the theoretical and actual induced drag polars plotted in linearized form: C_L^2 versus C_D. In other words, it is the ratio of the effective and geometric aspect ratio. Simplified theoretical considerations often assume, however, that the profile and parasite drag are constant, that is, the total drag polar is parallel to the actual induced drag polar. Hence, it is a general practice to express the span efficiency as the ratio between the slopes of the theoretical induced drag polar and the total drag polar. This is, however, not precise, since in practice both the profile and parasite drag are subject to change with the lift coefficient, and the slope of the total drag polar is accordingly different from that of the actual induced drag polar.

In the case of the Horten IV, using the slope of the total drag polar, the span efficiency appears to be 53 per cent, however, the actual span efficiency, using the induced drag increment, is 76 per cent.

Fig. 5



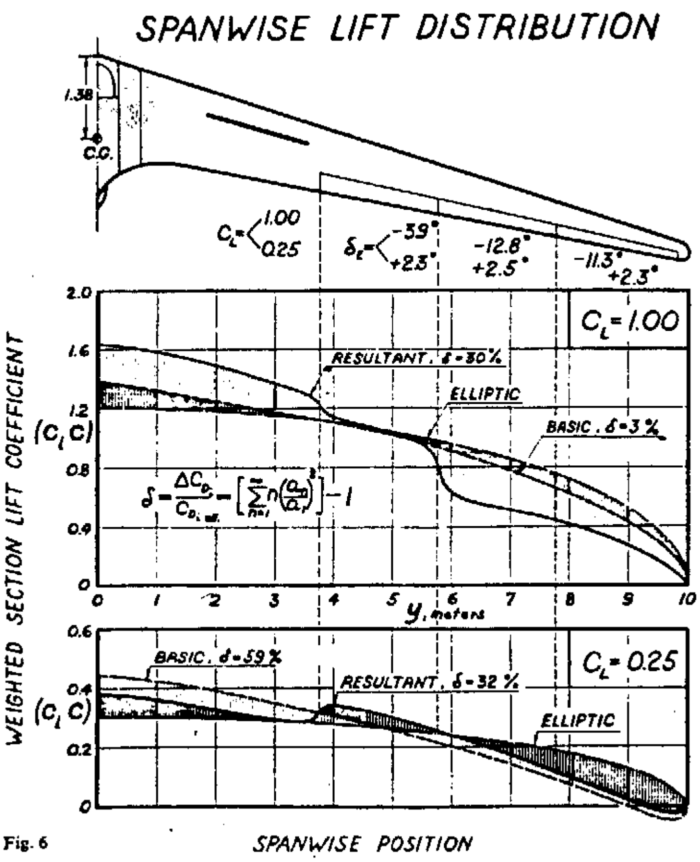


Fig. 6

The Maximum Lift Coefficient

A further weakness of the Horten IV, which was not clearly understood, is the low maximum lift coefficient. This can be cleared also by studying the lift distribution at minimum speed.

In Figure 11, the actual local lift coefficient is plotted along the span for $C_L = 1.125$. The peak value, $c_{l_{max}} = 1.36$, occurs at about 35 per cent of the half span, that is, somewhat inboard of the elevons. Tuft observations revealed that intense separation exists at the same place when the plane flies at the minimum speed. This means that the stall is initiated there, that is, the local lift coefficient reaches its maximum possible value. Since $c_{l_{max}}$ for a given airfoil depends primarily upon the Reynolds number, the maximum available lift coefficient for the rest of the wing can be estimated. Accordingly, $c_{l_{max}} \approx 1.4$ for the wing root ($Re = 1.7 \times 10^6$) and $c_{l_{max}} \approx 1.00$ for the tip ($Re = 0.4 \times 10^6$). In Figure 11, the maximum available local lift coefficient is also indicated. The difference between this and the curve of actual lift coefficient, designated as lift reserve, indicates the margin of safety against tip stall.

As can be seen, the local lift coefficient reaches the limit of the stall once at the third half span and once more at the outer end of the inboard elevon, but remains far below the limit on the outboard part of the wing due to the highly deflected control surfaces. This implies a great safety margin against tip stalling, but simultaneously results in a considerable loss in lift. This is why the resultant maximum lift coefficient, $C_{L_{max}} = 1.125$, is so low although the airfoil itself has a normal $c_{l_{max}} = 1.3$ to 1.4, at the Reynolds numbers concerned. For comparison, the lift coefficient distribution for the wing without control deflection is given also in Figure 11. This shows that the local lift coefficient would exceed the available limit over the outer portion of the wing, resulting in tip stall. Consequently, some negative control deflection at the tips is necessary, however, much less would be sufficient to provide favourable stall characteristics than actually is applied.

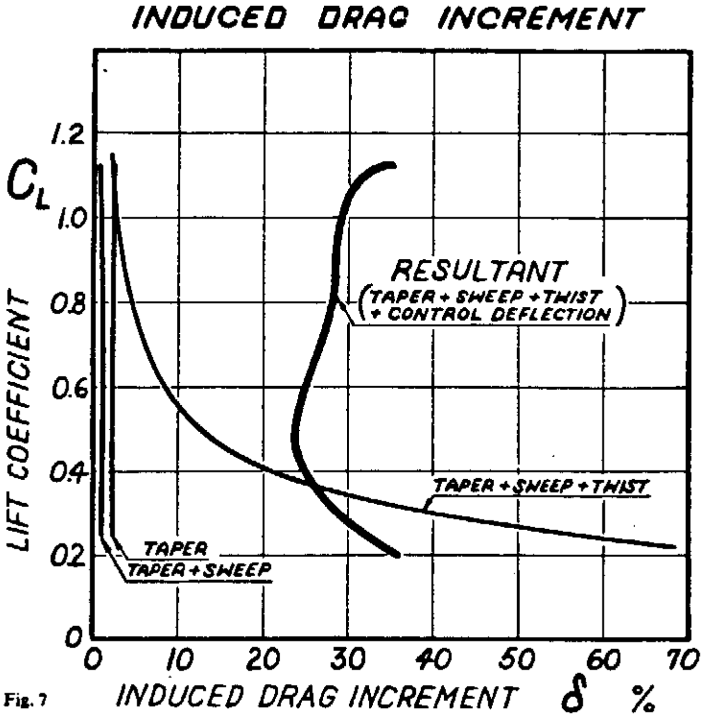


Fig. 7

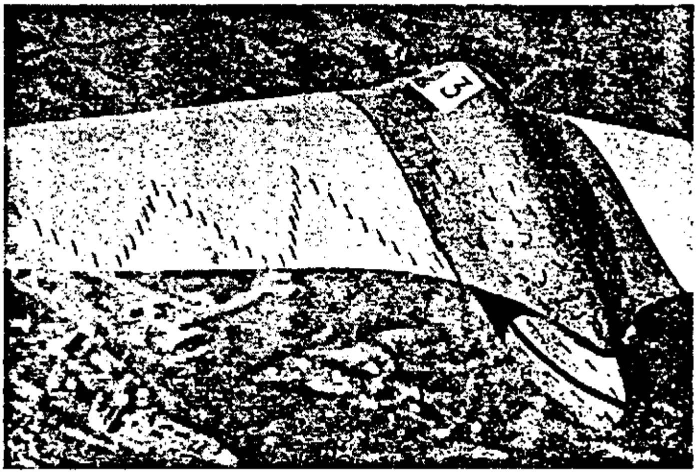


Fig. 8a V = 70 km/h $C_L = 0.825$

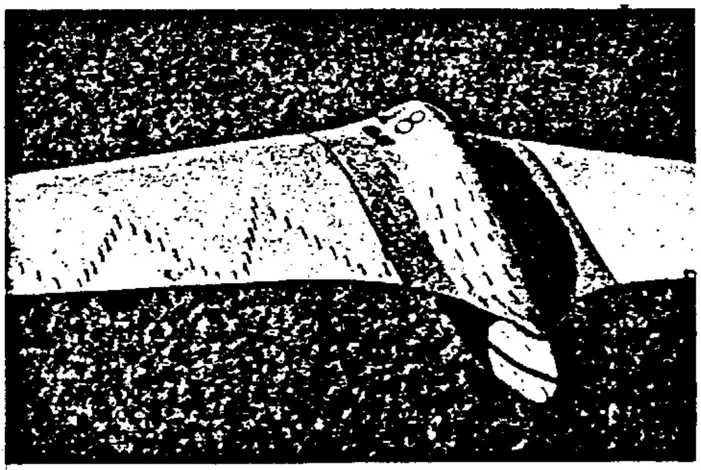


Fig. 8b V = 100 km/h $C_L = 0.41$

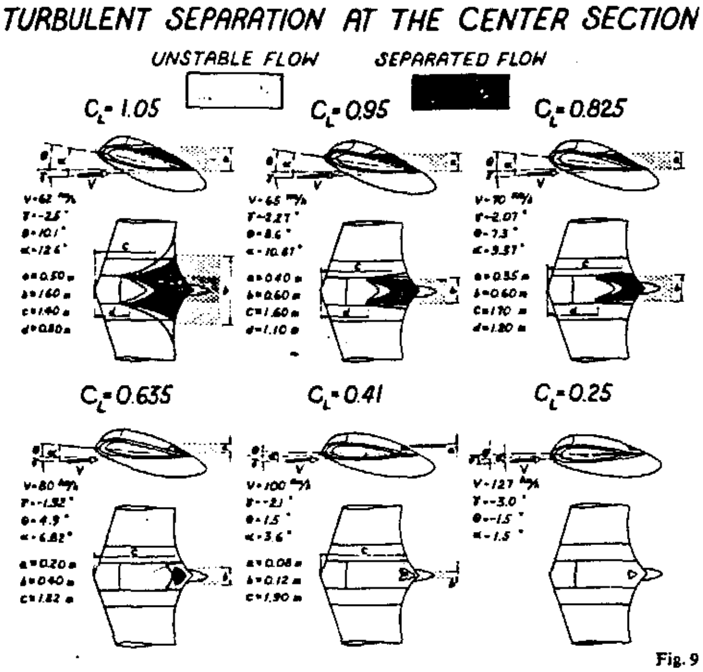


Fig. 9

Possible Performance Improvements

On the basis of the foregoing drag analysis, the possibilities of performance improvement will be discussed below. This is based on a calculation in which we assumed several successive improvements in the drag components, which are believed reasonable in the present state of development. These improvements are the following:

(1.) A reduction of the profile drag to the level of the present laminar airfoils. For comparison, the profile drag polars of the Horten IV and the Phoenix are presented in Figure 12. Also, two imaginary polars for the Horten IV, used in the present calculation, are shown. One of severely increasing drag, like the original; another, which has nearly constant drag up to $C_L = 0{,}8$. The latter could be achieved only if the extent of the elevon surfaces, or their deflection providing the trim, were greatly reduced by some means.

(2.) The induced drag increment, which is 25 to 30 per cent, could be reduced to at least 8 to 10 per cent if the excessive twist and large negative control deflection were reduced. Variable sweep, C.G. position, or twist might be a solution to this probleme.

(3.) The parasite drag is considered completely eliminated by providing a separation-free pilot compartment.

Figure 13 demonstrates the result of these improvements on the gliding performance. Curve No. 1 is the present state; Nos. 2, 3 and 4, show the performance if only one of the three drag components were improved at one time. Thus, the importance of the several modifications can be seen clearly. Namely, the complete elimination of the parasite drag would affect the performance mostly at low speeds, and the best gliding ratio would be barely increased (Curve No. 2). The reduction of the induced drag increment to 10 per cent would increase the best gliding ratio from 29.5 to 32 only (Curve No. 3). But a considerable improvement follows when the profile drag is reduced. Curve No. 4 was obtained by using the imaginary profile drag polar marked as "A" in Figure 12. The best gliding ratio rises to 40, and the performance at high speed, that is, the penetration ability, is greatly increased. Curves No. 5 and 6 show the improvement, if in addition to the above profile drag reduction, the parasite drag were eliminated and the induced drag were decreased in the formerly described manner. In this case, a remarkable improvement appears in the low speed region, and the best gliding ratio becomes 41.5 and 43.5 respectively. Finally, the Curve No. 7 represents the ultimate performance which could be achieved with the other imaginary profile drag polar marked "B" in Figure 12, naturally assuming the above mentioned improvements in induced and parasite drag. In this case, the best gliding ratio would be 48, a really phenomenal one.

Conclusions

The present investigation has basically cleared the conditions by which the performance of the Horten IV was limited. However, a large margin of improvement seems to be possible by means of proper drag reduction. An up-to-date flying wing of the size of the Horten IV should be able to reach a best gliding ratio of nearly 50 to 1. In the case of one of the very best conventional designs, like the Phoenix, such a high performance seems to be feasible only if extensive boundary layer control were applied. This verifies that the flying wing design is not an obsolete idea, but is worthy of further development.

Fig. 10

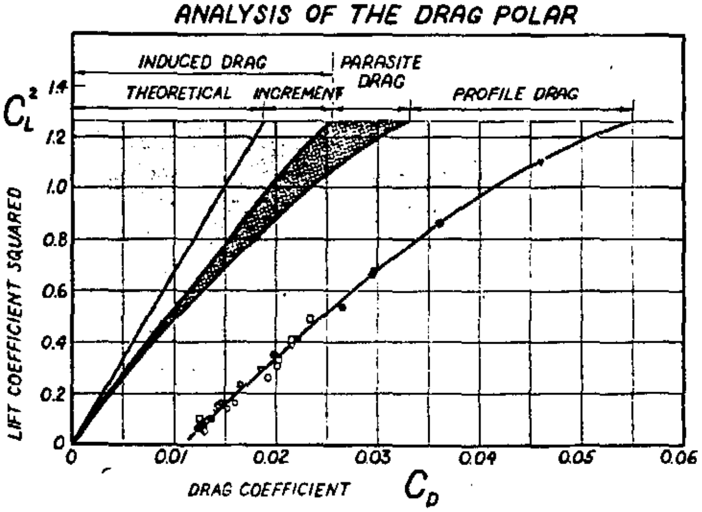
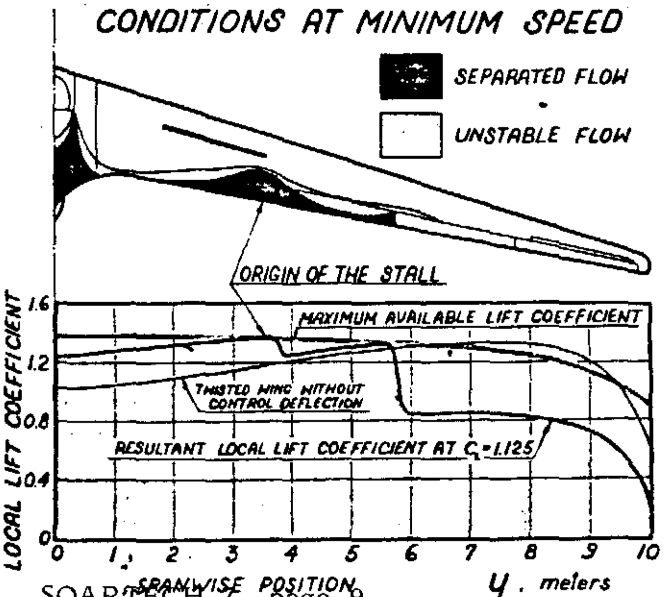


Fig. 11



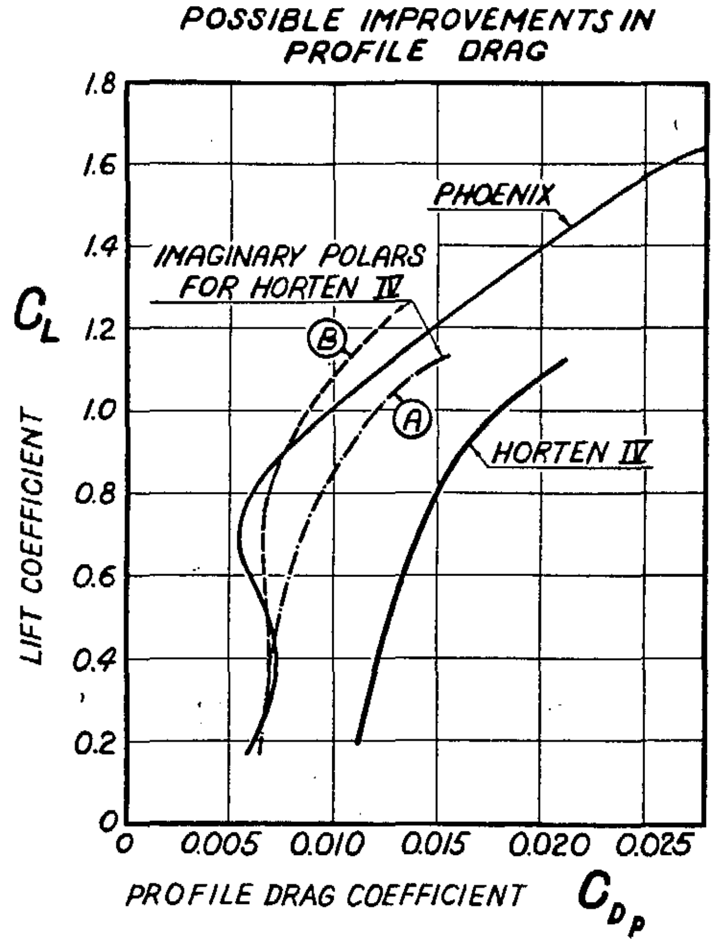


Fig. 12

It is beyond the scope of this paper to deal with the stability and control characteristics in detail, nevertheless, the author wishes to note that, in his opinion, the handling of the Horten IV is not essentially more difficult than that of any other high performance sailplane. The extremely good natured stalling and circling characteristics, as well as the excellent landing manoeuverability are to be noted especially. The prone position of the pilot is believed to provide a more natural sensation of flight than the conventional sitting position; in addition, it provides incomparable visibility for landing and navigation. On the other side of the balance, however, the marginal directional stability, unusual response for rudder control coupled with pitch, and above all, the wing tip flutter, appearing above 140 km/h, should be noted.

Drawing the final conclusions, we summarize once more the major deficiencies of the Horten IV and outline the possible ways of improvement in Table II.

Two of the suggested improvements are of primary importance, that is, the use of a low drag laminar airfoil and the elimination of large control deflection by some means, for example, by variable sweep or center of gravity. The variable sweep seems to be fairly practical, however, a more detailed consideration is necessary to find out which would be the more favorable way. To do this, of course, the stability and control characteristics are to be taken into consideration also.

Since the keystone of the performance improvement lies in the use of a laminar airfoil, this, in case of the Horten IV, would mean a complete reconstruction of the airframe. Therefore, further development seems more reasonable through a new design, in which all the experiences gained so far as well as the latest technology of construction could be utilized.

This does not mean, however, that there is no further use for the Horten IV as far as further research is concerned. For example, for the sake of further development it would be necessary to evaluate the stability and control characteristics, as was done for the performance. Moreover, it would be very useful to make an experiment on variable sweep, before adopting it for a new design and the Horten IV seems to be suitable for this experiment.

We, at Mississippi State University, have planned to continue this work through further evaluation and study toward a new flying wing design, in which the brave old Horten IV would be reincarnated. The tragic death of Dr. August Raspet, who was the leading spirit in this aspiration, however, has made the chances of realizing this plan very uncertain.

Symbols

A.C.		Aerodynamic center
b	m	Wingspan
c	m	Chord length
C. G.	–	Center of gravity
C_D	–	Total drag coefficient
C_L	–	Resultant lift coefficient
c_l	–	Section lift coefficient
C_{D_p}	–	Resultant profile drag coefficient
c_{d_p}	–	Section profile drag coefficient
C_{D_i}	–	Induced drag coefficient
e	–	Span efficiency
Re	–	Reynolds number
S	m_2	Wing area
V	km/h	Calibrated airspeed
W	kg	Gross weight
w	m/sec	Sinking speed
y	m	Distance perpendicular to the symmetry axis
α	deg.	Angle of attack
δ	–	Factor of induced drag increment
δ_E	deg.	Elevon deflection angle
ε	–	Gliding ratio
γ	deg.	Glide path angle
Θ	deg.	Pitch angle
λ	–	Geometric aspect ratio b^2/S
λ_{eff}	–	Effective aspect ratio

Table I

Measured Aerodynamic and Performance Data

		DFS[1]	MSU[2]
$C_{D_{min}}$		0.01175	0.0125
$C_{L_{max}}$		1.17	1.125
$\frac{dC_L}{d\alpha}$	Rad^{-1}	–	4.35
$\frac{C_{L_{max}}}{C_{D_{min}}}$		99.5	90
$\varepsilon_{max} = \left(\frac{L}{D}\right)_{max}$		31.5	29.5
e		63%	53%
λ_{eff}		13.4	11.3
w_{min}	m/sec	0.59	0.70
$V_{w_{min}}$	km/h	60.0	70.0
V_{min}	km/h	52.0	59.5
$V_{\varepsilon_{max}}$	km/h	76.0	82.0
$V_{\varepsilon = 20}$	km/h	130.0	126.0

[1] Data reduced from DFS actual tested gross weight W = 325 kg to W = 366 kg. C.G. position is unknown

[2] Actual tested gross weight W = 366 kg. C.G. position 1.38 meters from the nose point (See figure 5)

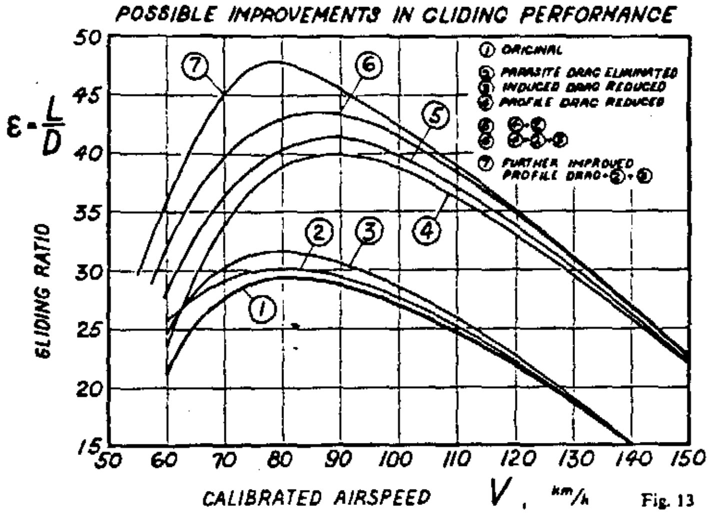


Fig. 13

Table II

Summary of the Evaluation of Horten IV concerning the Performance

Deficiency	Reason	Possible Way of Improvement
High profile drag	(1.) Obsolete airfoil	Use of laminar airfoil
	(2.) Disturbance of the airfoil by control surfaces, dive brakes and drag rudders	Smaller but more effective control surfaces with sealed gap. Different arrangement of dive brakes and rudders.
	(3.) Excessive control deflection	Variable sweep or C.G. to provide trim
	(4.) Low Reynolds number at the tip due to high taper ratio	Moderate taper ratio
High induced drag	Excessive twist control deflection, and taper	Variable sweep or C.G. to provide trim, less taper
High parasite drag	Separation from the canopy	Different canopy arrangement
Low maximum lift coefficient	Excessive control deflection, excessive taper	Variable sweep or C.G. and, perhaps, variable twist, less taper

Main Dimensions of the Horten IV[1]

Span	20	m
Wing area	18.8	m^2
Aspect ratio	21.3	
Dihedral	5	degrees
Sweep-back (¼ chord line)	17	degrees
Twist	7.1	degrees
Wing root chord	1.55	m
Wing tip chord	0.28	m
Taper ratio	5.55	
Airfoil sections	Reflexed, individual design	
Total area of elevon surfaces	3.16	m^2
Ratio of the elevon surfaces to the total wing area	16.8	%
Total wetted area	41	m^2
Ratio of the wetted area to the total wing area	2.18	
Empty weight (present condition)	266	kg
Gross weight (recent flight tests)	366	kg
Wing loading (recent flight tests)	19.5	kg/m^2

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[1] Most of the data are taken from Reference 1

Acknowledgements

This work was done under the sponsorship of the United States Army Transportation Command and Office of Naval Research. Dr. August Raspet, Head of the Aerophysics Department, took the initiative in this study and gave full support and inspiration. A special appreciation is due to Mr. Rudolf Opitz, who saved the Horten IV from deterioration, rebuilt and flew it with remarkable success in the U.S. National Contest of 1951, as well as in the early flight tests at Mississippi State University, then introduced the author to flying the plane and gave over much of his vast experience on flying wings.

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(Swiss Aero Review 1961/1)

"Twinkle, twinkle little bat;
How I wonder where you're at ..."

---- The mouse at the Mad Hatter's tea party

---- from the Walt Disney movie **Alice in Wonderland**

Gliding Flight of the Dog-Faced Bat *Rousettus aegyptiacus* Observed in a Wind Tunnel

by C. J. Pennycuick

Department of Zoology, University of Nairobi

INTRODUCTION

Tilting wind tunnels have been used to study the gliding performance of the pigeon *Columbia livia* (Pennycuick, 1968), and the lagger falcon *Falco jugger* (Tucker & Parrot, 1970). In both cases the bird was trained to fly in the tunnel in such a way as to remain stationary relative to the apparatus, so that its flying speed was equal to the wind speed, which was under the control of the experimenter. The bird's best gliding angle at any particular speed could be found by adjusting the tilt of the tunnel to the flattest angle which the bird was just able to glide. The present paper describes similar experiments on the bat.

MATERIAL

All the measurements were made on a male *Rousettus aegyptiacus* (*Megachiroptera*: *Pteropodidae*), which was only individual out of an initial group of six which learned to fly in the tunnel. The bats were caught in a cave near Lake Nabugabo in Uganda, where some thousands of them roost, with the help of Dr. F. A. Mutere and members of the East African Virus Research Institute at Entebbe, to whom I am most grateful. The bats thrived in captivity on a diet of pawpaw and banana, varied occasionally with other soft, sweet fruits. The bat which eventually learned to fly in the wind tunnel performed best when its diet was adjusted so as to keep its mass at about 118-120 g (on an *ad lib* diet its mass rose to about 140 g).

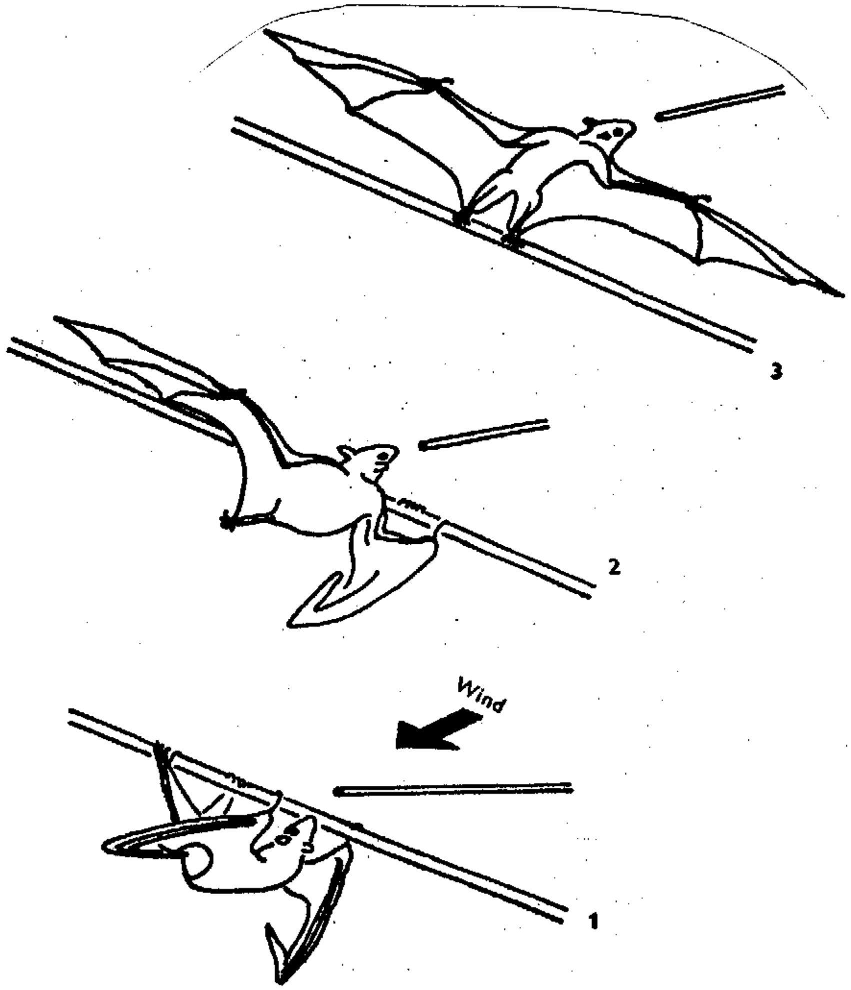
METHODS

Wind Tunnel

The same wind tunnel was used as that described by Pennycuick (1968), but it was moved from its former site at Bristol to the University of Nairobi prior to the experiments. The working section was octagonal with a diameter of 1 m, and the angle of tilt could be adjusted from -2° to +30° above the horizontal. The tunnel was of open-jet blower layout, the working section being surrounded by a wire mesh cage.

Training

The training method was basically the same as that used for pigeons by Pennycuick (1968). Training flights and experiments were carried out at dusk or soon after, at which time the bat became active and would go to considerable lengths to obtain a food reward. Banana proved to be by far the most effective inducement.



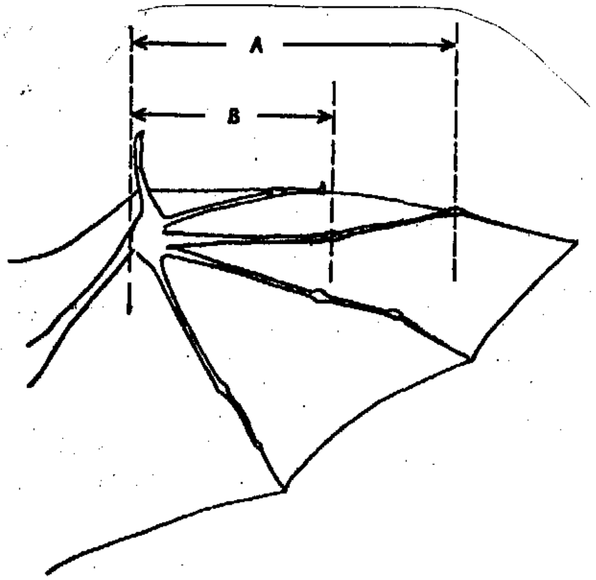
Text-fig. 1. Stages in training the bat to take off from the perch. After reaching stage 3 the bat eventually learned to release its hold on the perch and fly free. The feeding tube was hand-held during training

The first stage of training was to tame the bat until it would fly to the hand for food. Learning to fly in the wind tunnel was somewhat more difficult than for a pigeon, because the bat was unable to stand upright on a perch, and had first to recover from its normal inverted stance before it was in a position to take off.

The bat was first of all suspended from a wooden perch, of 13 mm diameter circular cross-section, which spanned the working section of the tunnel. The reward was offered by means of a Perspex tube of 4 mm inside diameter, filled with banana pulp, which could be extruded from the end as required by pushing it out with a piston. The bat was first rewarded whenever it raised its head above the *downwind* side of the perch, and it soon learned to spread one wing above the perch in order to raise itself a little higher (Text-fig. 1). Eventually it could lift its body right above the perch suspending its weight from its wings, but still clinging to the perch with its feet. Two bats were trained up to this stage, of which one learned to release its hold on the perch after about 10 weeks of almost daily training, and after a further 3 months could fly well enough in the tunnel for measurements to be made. The other one never learned to let go of the perch, and died after about 4 months of training.

Measurement of Best Gliding Angle

When the bat was proficient at flying in the tunnel, the food dispenser was fixed so that the bat had to hover just above the center of the tunnel in order to feed from it. The bat would climb along the perch to the center of the tunnel, then take off and fly to the feeder, where it would hover until its mouth was full of banana. It would then fly to the side and land on the wire mesh surrounding the working section, where it would chew and swallow the food, before returning to the perch for another flight. Thus the individual



Text-fig. 2. The scale of each photograph was determined by measuring two reference lengths on digit 3. Length A was measured from the proximal side of the carpal joint to the distal end of the first phalanx, and length B from the proximal side of the carpal joint to the distal end of the metacarpal.

flights were brief, varying in duration from about 5 seconds to 1 minute, it was not feasible to adjust the wind speed or the tunnel tilt during a flight, Instead, the speed was kept constant throughout each session, and the tilt angle was adjusted between flights. Each flight was then then scored as either 'definitely able to glide', or 'definitely unable to glide' or 'doubtful'. Because the bat's flight was never as steady as that of a pigeon, it was often difficult to be sure whether it was or was not able to glide, and the true best gliding angle is considered to fall on the borderline between the 'definitely able' and 'doubtful' categories.

Photography

An overhead camera was mounted on a boom above the working section, looking perpendicularly to the airflow, as described by Pennycuick (1968). Initially a Canon Dial half-frame 35 mm camera was mounted in this position, and used for determining wing span and area. Owing to the unsteadiness of the bat's flight, however, it was difficult to be sure from a single photograph that the wings were in a symmetrical gliding attitude, which made the determination of span and area somewhat doubtful. To overcome this difficulty a White 'Stereo Realist' camera was substituted for the Canon Dial. This instrument consists of two separate cameras mounted in a single casting, with their axes parallel and 7.0 cm apart, and with their controls coupled together, so that two 24 X 23 mm negatives are taken simultaneously on 35 mm film. These were enlarged to make stereo pairs of half-plate (12 X 16.5 cm) prints, which were viewed with a Wild mirror stereoscope. Only those which showed an approximately level and symmetrical attitude of the wings were used to determine wing area.

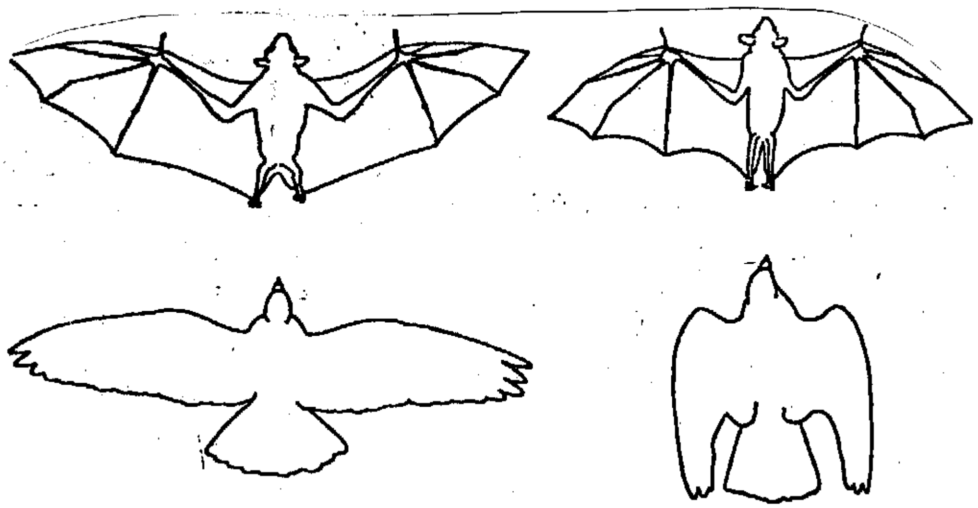
To determine the scale of each photograph two measurements were made on digit 3 of each wing, as shown in text-fig. 2. This part of the wing was approximately horizontal in all the photographs used. The four estimates of scale so obtained from each photograph were averaged to give the factor used for converting measurements made on the photograph up to life size.

Mechanics of the Wing Compared with that of the Pigeon

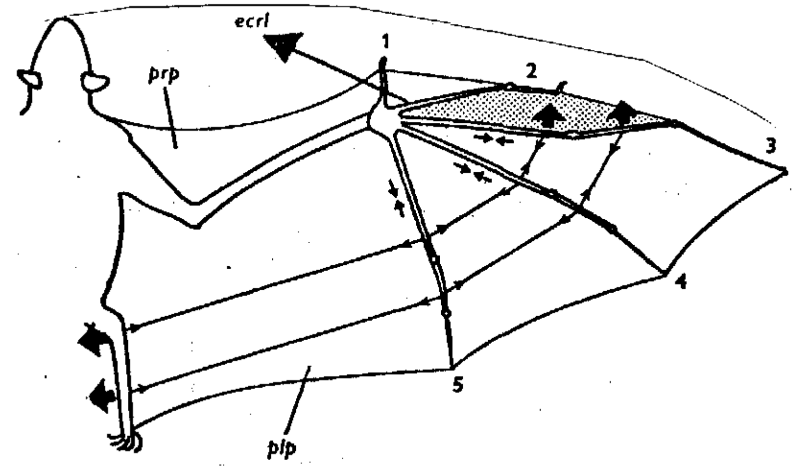
Changes of Planform

The stereo photographs provided 24 measurements of wing span and area at speeds from 5.5 to 10.0 meters/second. The correlation coefficient between wing area and speed was -0.1713, which is not significantly different from zero. That between wing span and speed was -0.3974, which is just significant at the 5% level, using a one-tailed test. The corresponding correlation coefficients for the 29 measurements on the pigeon Columbia livia given by Pennycuick (1968) are -0.8444 and -0.9492 respectively which are both highly significant ($P< 0.001$). The drastic decrease of wing span and area with speed, which is so conspicuous in gliding birds (Pennycuick, 1968; Tucker & Parrot, 1970), was thus not evident in the bat.

The range of variation of the wing area available to the bat was actually somewhat greater than this observation would suggest. The greatest wing area seen in any of the photographs was 566 cm^2 , and the least 399 cm^2. That is, the bat could reduce its wing area to 70% of the maximum, whereas the pigeon's minimum wing area was 62% of its maximum. Tracings of the

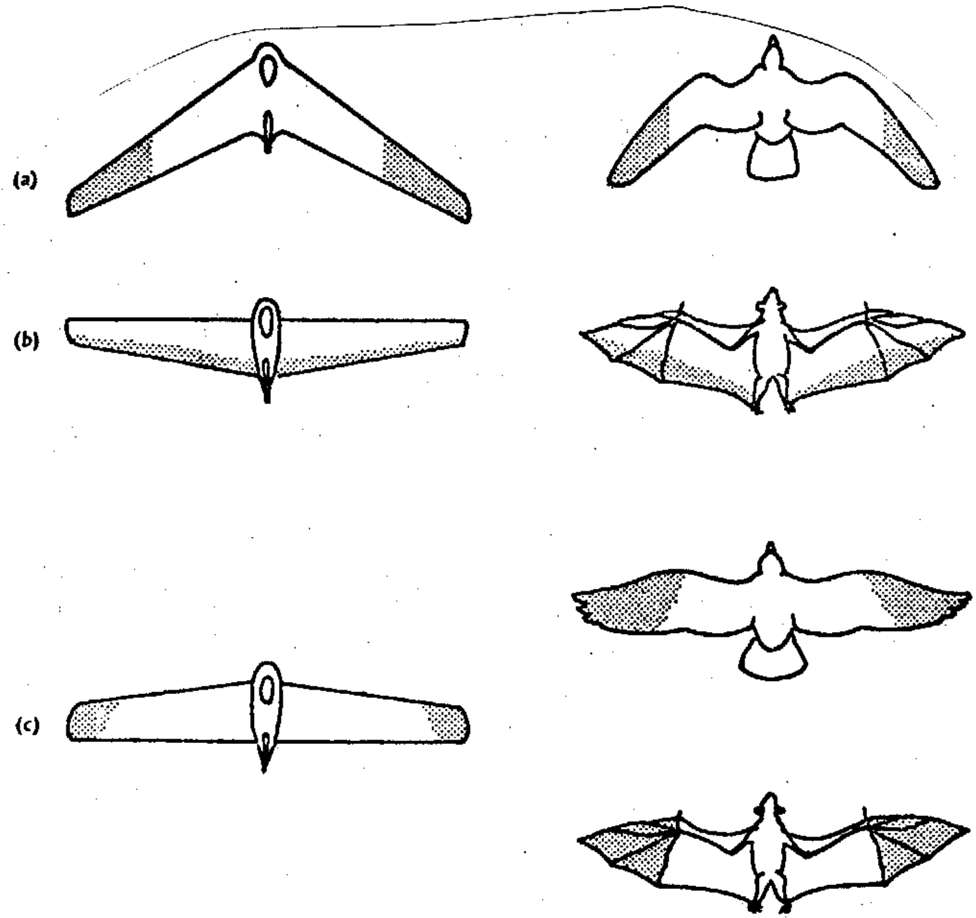


Text-fig. 3. Maximum and minimum wing area in bat and pigeon (see text).



Text-fig. 4. Mechanics of the bat's wing. The stippled area is the dactylopatagium minus, which together with those parts of digits 2 and 3 which enclose it, forms a rigid unit, resistant to bending in the plane of the membrane (Norberg, 1969). This complete unit is pulled forward by the extensor carpi radialis longus muscle, of which the direction of pull is indicated by the large arrow marked ecrl. This forward pull is transmitted to the membrane attached to the posterior side of digit 3 (broad arrows), and thence through the outer wing panels and the plagiopatagium (plp), to be balanced by an opposing inward pull exerted by the hind leg (broad arrows). The lines with open arrowheads represent tension paths through the patagium, which change direction at digits 4 and 5; the bones of these digits are therefore loaded in compression (small solid arrows), as is digit 3 also. The leading edge of the propatagium (prp) is held down by the tendon of the occipitopollicalis muscle, which originates on the back of the skull (Norberg, 1970).

two photographs in question are compared in Text-fig. 3, from which it can be seen that the reduction of area is achieved by reducing between the bones supporting the wing, except that between metacarpals 2 and 3. Thus in the attitude of smaller area the humeri are more swept back while the radius is more swept forward, so allowing the propatagium to contract in the spanwise direction, and the fifth metacarpal is more nearly parallel to the body axis so that the plagiopatagium does the same. The angles between metacarpals 3, 4 and 5 are reduced, allowing the outer wing panels to contract perpendicularly to the bones.



Text-fig. 5. Methods of achieving longitudinal stability in tail-less airplanes, with suggested equivalents in birds and bats. (a) Sweepback-with-washout (stippled areas twisted in nose-down sense); e.g. Horten flying wings. (b) Reflex camber (stippled areas deflected upwards), e.g. Fauvel flying wings. (c) Diffuser wing tips (stippled areas deflected downwards), e.g. Northrop flying wings. The mechanisms of these different systems are eplained by Weyl (1945a).

The mechanics of the wing of *Plecotus auritus* have been analyzed by Norberg (1970) and the anatomy is similar in *Rousettus* (Dr. U. M. Norberg, pers. comm.). Digits 2 and 3 are interconnected in a special way (Norberg, 1969), and together with the small piece of membrane enclosed between them (dactylopatagium minus), constitute a relatively rigid unit, which is resistant to bending in its own plane. The second metacarpal, and hence the whole of this unit, is pulled forward by the extensor carpi radialis longus muscle, and this pull is transmitted through the wing membrane across digits 4 and 5, and thence through the plagiopatagium to the hind leg. The entire wing is thus to be thought of as a single unit under tension, with the membrane stretched between digit 3 and the hind leg, digits 4 and 5 acting as compression members altering the direction of the tension forces (Text-fig. 4). The tension in each of the outer wing panels, and the plagiopatagium, must be approximately equal, and is maintained by elastin fibers within the wing membrane, running parallel to the direction of stretch. When digits 2 and 3 rotate posteriorly, the fibers in all three panels shorten and the skin crinkles as the area of the membrane is reduced. Because of this arrangement the areas of the outer wing panels and of the plagiopatagium are interdependendent and have to be adjusted together.

In the bird wing, on the other hand, each flight feather is an independent structure capable of resisting bending moments both in the plane of the wing and normal to it. By overlapping the feathers, the area and planform of the distal part of the wing can be drastically altered without affecting the structural strength of the proximal part. The wing shape characteristic of fast-gliding birds, where the manus is rotated sharply backwards, whilst keeping the inner part of the wing partially extended, would be mechanically impossible for a bat, because it would lead to collapse of the outer wing panels, and this in turn would lead to collapse of the plagiopatagium as well. Thus, while the pigeon in a very fast glide can rotate the morphological 'leading edge' of its wing panel parallel to the direction of flight, and thus reduce its wing span to 37% of its maximum value, the bat could not do this, and was only able to reduce its span to 83% of the maximum (Text-fig. 3).

Table 1. Technical data for the bat at its average weight of 1.16N and at different wing areas

	Minimum area	Average area	Maximum area
Wing area (m^2)	0.0399	0.0462	0.0566
Wing span (m)	0.461	0.4940	.554
Aspect ratio	5.32	5.28	5.42
Wing loading (Nm^{-2})	29.1	25.1	20.5

Although the structure of the bat's wing limits its versatility in one way, it extends it in another, since the arrangement of the fingers allows much more control over the profile shape of the manus than can be achieved with the unjointed feathers of a bird, and this feature is no doubt responsible for the extreme agility of bats when maneuvering at low speeds.

Wing profile shape

The stereo photographs show that the propatagium is always sharply cambered in flight (Pls. 1, 2). The arrangement is the same as that described in the microchiropteran *Plecotus auritus* by Norberg (1969), the leading edge of the propatagium being held down by the occipitio-pollicalis muscle, which originates on the on the posterior surface of the skull, and whose tendon runs along the anterior edge of the propatagium via the metacarpal of the thumb to the second metacarpal, or thereabouts (Dr. U. M. Norberg, pers. comm.). This is a muscle unique to bats, which is analogous in action to the tensor patagii muscles of birds.

The upper surface of the proximal part of the wing is not as smooth as in birds. The humerus and radius both project above the wing surface (Pl. 1a), and most probably serve to generate turbulence in the boundary layer. Such an adaptation is readily understandable in relation to the results of Schmitz (1960), who found that in the Reynolds Number range in question, a lift coefficient as high as 1.5 could only be obtained if turbulence were artificially introduced into the boundary layers of model wings. The wing surface is also rendered rather wavy by the fact that both the propatagium and the plagiopatagium must bulge upwards to transmit lift to the humerus and radius, so that troughs tend to appear along the anterior and posterior margins of these bones. Almost interesting feature is that the posterior edge of the outer wing panels is normal deflected upwards in steady gliding flight, owing to an upward deflexion of the joints at the distal ends of the fourth and fifth metacarpals, and also those between the first and second phalanges of the same digits. Sometimes the posterior edge of the plagiopatagium is deflected upwards as well. This latter effect appears to be under control of the plagiopatagialis proprii muscles, a group of about 10-12 muscle bundles (visible in Pls. 1b, 2), which run antero-posteriorly in the plagiopatagium, posterior to the radius, but without attaching to any part of the skeleton. It appears that when these muscles contract the plagiopatagium becomes S-shaped in section, riding up at the posterior edge, whilst when they are relaxed the plagiopatagium bulges convex upwards over its whole extent (Pl. 2).

The upturned trailing edge is most probably concerned with longitudinal stability and control. Since neither birds nor bats depend on tails for stability, they are to be classified with tail-less airplanes in this respect. The principles of stability in such aircraft are well known, and have been explained at length by Weyl (1945 a, b), who lists four basic ways in which stability can be obtained without using a tail: (1) a combination of sweepback with washout (i.e. twist of the outer part of the wing in the nosedown sense); (2) upward deflexion of the trailing edge of the wing; (3) 'diffuser wing tips', in which the wing tips are bent downwards about an oblique axis: this arrangement confers directional as well as longitudinal stability; (4) sweepforward-with-washin, the opposite combination to (1).

The first three types of stabilizing systems and their suggested use in birds and bats are summarized in Text-fig. 5. It would appear that both birds and bats have diffuser wing tips when gliding slowly with their wings fully spread. In fast gliding flight birds rotate the manus posteriorly whilst keeping the proximal part of the wing extended, and then most probably depend on sweepback-with-washout for stability. Bats cannot rotate their wings in this way, and appear instead to supplement their diffuser tips by upward deflexion of the trailing edge.

The fourth stable arrangement listed above, sweepforward-with-washin, has been tried in aircraft but has certain disadvantages. Neither birds not bats seem to use it, although it would be mechanically possible for both to do so.

Longitudinal control, as opposed to stability, is apparently achieved in gliding birds by variations of sweepback, so shifting the center of lift forward or back with respect to the center of gravity (Pennycuick & Webbe, 1959). The amount of such movement available to a gliding bat is much more limited, however, and *Rousettus* appears to supplement this action by using its plagiopatagialis proprii muscles as an elevator control. Increasing the upward deflexion of the trailing edge, as in Pl. 2b, would give rise to a nose-up pitching moment, and vice versa.

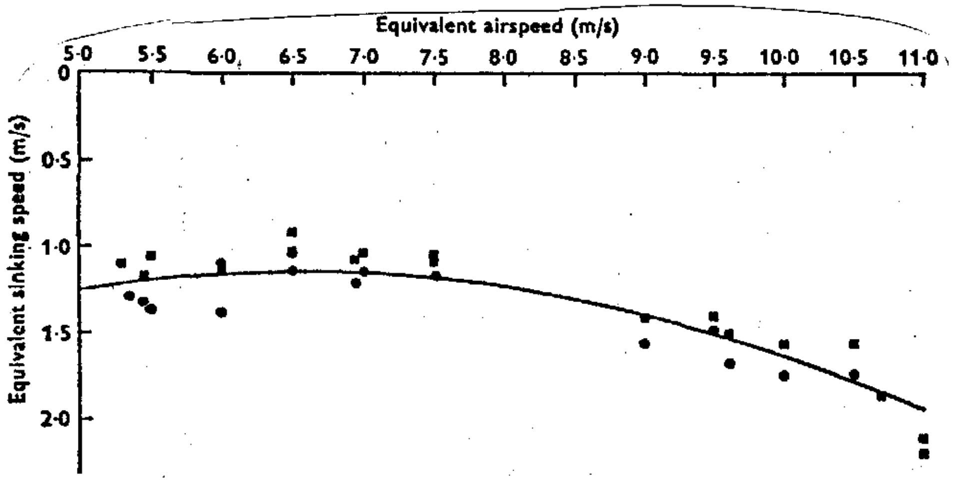
GLIDING PERFORMANCE

Speed range

Text-fig. 6 shows the results of 33 determinations of best gliding angle at equivalent airspeeds between 5.5 and 11.0 meters/second. For any particular occasion the flattest angle at which the bat could definitely glide is plotted, and also the steepest 'doubtful' observation; on a few occasion observations in only one category were obtained. The results are expressed in the form of a conventional glide polar, that is, a plot of equivalent sinking speed against equivalent airspeed.

The bat's minimum gliding speed when at its normal weight was 5.3 meters/second, and its maximum lift coefficient was about 1.5. The highest speed at which measurements were made was 11.0 meters/second ($C_l = 0.33$). At this speed the bat had difficulty in controlling its position in flight, and also in controlling its wings when clambering on the perch or the sides of the cage, and so flight at higher speeds was not attempted because of danger to the bat. The speed range between 7.5 and 9.0 meters/second was also avoided because of vibration caused by a mechanical resonance in the tunnel support system.

The Reynolds Number range, based on mean chord, was from 3.26×10^4 to 6.79×10^4.



Text-fig. 6. Glide polar, from wind-tunnel observations of best gliding angle. Circles: flattest angle at which bat was definately able to glide. Squares: steepest angle at which bat doubtfully able to glide (see text).

The maximum lift coefficient given for the pigeon by Pennycuick (1968) was 1.3, but this figure was based on the sum of wing area and tail area, on the grounds that the tail appeared to contribute some lift. the maximum lift coefficient based on wing area alone would be 1.5, and it is perhaps more consistent to compare maximum lift coefficients on this basis. Tucker & Parrot's (1970) figure of 1.6 for the lagger falcon *Falco jugger* is also based on wing area alone, and in the case of the bat there is of course no choice, since it has no tail, aerodynamically speaking. Thus there seems to be little difference between bat and bird wings in this particular.

Regression analysis

Owing to the absence of any marked changes of wing shape at different speeds the results shown in Text-fig. 6 (to some of which no reliable measurements of wing area or span can be attached) can reasonably be analyzed on the assumption that wing planform is independent of speed. A curve of the form

$$V_z = \frac{b}{V} + gV^3, \qquad (1)$$

can then be fitted through data, where V_z is the equivalent sinking speed, V is the equivalent airspeed and b and g are constants. The estimates of the constants calculated by the least-squares method were

$$b = 5.51,$$

$$g = 1.07 \times 10^{-3},$$

and the curve obtained by substituting these values in equation (1) is plotted along with the data in text-fig. 6.

As explained by Pennycuick (1971) the regression *b* can be used to estimate the span efficiency factor *k*, defined by the relationship

$$k = \frac{C_{di} p A}{C_l^2}, \qquad (2)$$

where C_{di} is the induced drag coefficient, C_l is the lift coefficient and *A* is the aspect ratio. *g* gives an estimate of C_{do}, the drag coefficient (referred to wing area) at zero lift. Using average values for the weight, aspect ratio and wing area (Table 1), the estimates of these quantities were

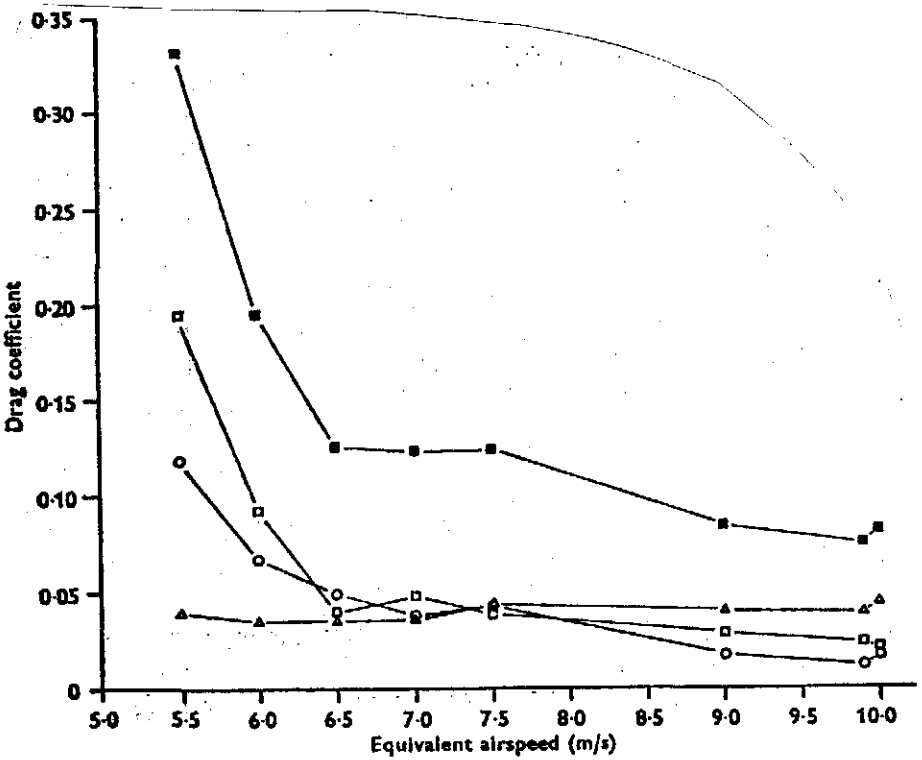
$$k = 2.23,$$

$$C_{do} = 0{,}0440.$$

In the ideal case of elliptical lift distribution *k* would be 1. In airplane wings *k* is commonly about 1.1 or 1.2, but a value of 2.23 for *k* would imply a degree of inefficiency unknown in aeronautical engineering.

The very high estimate of *k* results from the assumption, implicit in the regression analysis, that the drag rise observed at high lift coefficients (low speeds) is entirely due to induced drag, and that the wing profile drag coefficient is independent of the lift coefficient. An estimate of this (supposedly constant) wing profile drag coefficient is obtained below by subtracting other sources of drag from the total drag. This can be regarded as an extreme assumption, the other extreme being to assume that *k* = 1, and that most of the low-speed drag increase is due to an increase of wing profile drag coefficient at high lift coefficients. These two extreme interpretations will be more explicitly examined.

Interpretation 1: $k = 2.23$, $C_{do} = 0.0440$



Text-fig. 7. Drag coefficient analyzed on the assumption that the span efficiency factor = 1. Solid squares: total drag coefficient. Open circles: induced drag coefficient. Open triangles: body drag coefficient. Open squares: residual drag coefficient, attributed to wing profile drag. All drag coefficients are referred to wing area, measured from photographs.

First, if it is assumed that k really is 2.23, then C_{do} = 0.0440 represents an estimate of the sum of the body drag coefficient and the wing profile drag coefficient (both referred to wing area). The body drag was separately estimated from measurements on the wingless body of a dead Rousettus, which was frozen in the normal flying attitude and mounted on a drag balance, in the same way as was described for the pigeon by Pennycuick (1968). The drag of the body was found to be 0.0460 N at an equivalent airspeed of 7.70 meters/second. The mass of this bat when it died was 78.2 g, as compared to an average of 118 g for the individual on which the in-flight measurements were made. The drag measurement was therefore scaled up in proportion to the two-thirds power of the mass, giving an estimate of 0.0608 N for the body drag of the bat which flew in the wind tunnel. Referring this to the average wing area listed in Table 1, the body drag coefficient C_{dob} would be

$$C_{dob} = 0.0364 \, .$$

The wing profile drag coefficient C_{dow} can now be estimated as the difference between C_{do} and C_{dow}, so that

$$C_{dow} = 0.0440 - 0.0364 = 0.0076 .$$

Interpretation 2: k = 1

An alternative method of analysis is to partition the total drag coefficient into three fractions representing induced drag, body drag, and the remainder (attributed to wing profile drag), as was done for the pigeon by Pennycuick (1968). To do this, some assumption has to be made about k , for which an extreme low value is $k = 1$.

The results of analyzing the data in this way are shown in Text-fig. 7. the estimated induced drag, assuming $k = 1$, is now not nearly sufficient to account for the high total drag seen at very low speeds, and so it has to be assumed that the wing profile drag coefficient rises sharply at the lowest speeds to the rather high value of 0.19. A similar effect seen in the pigeon was attributed to changes of wing planform, but this explanation would be implausible in the bat.

Intermediate Interpretation

The first interpretation may be doubted, not only on account of the very high value of k, but also because the estimated wing profile drag coefficient C_{dow} is suspiciously low. Schmitz (1960) found that the minimum profile drag coefficient of a cambered plate tested at a Reynolds Number of 42,000 was 0.026, and it is perhaps unlikely that the rather irregularly shaped profile of the bat would achieve a C_{dow} less than a third of this, at approximately the same Reynolds Number. It is to be expected on the one hand that k would be substantially greater than 1, and on the other hand that C_{dow} would rise appreciably at high lift coefficients, so that the correct interpretation probably lies in between the extremes represented by $k = 2.23$ and $k = 1$. For instance, if one were to assume that $k = 1.5$, then C_{dow} would be about 0.018 at the higher speeds, rising to 0.13 in the neighborhood of the maximum lift coefficient. The question could probably be resolved by direct measurements of profile drag by the wake traverse method (Pankhurst & Holder, 1952), but unfortunately facilities were not available to try this.

CONCLUSION

The bat's best gliding angle (about 6.8) is slightly better than that of the pigeon, but otherwise its low-speed performance is closely similar. Owing to its inability to reduce the area of the outer part of the wing without collapsing the inner part, the bat is less successful at gliding very fast, and its speed range is not so wide as that of the pigeon. On the other hand, bats are most probably more maneuverable than birds in low-speed flight, because of their greater control over the profile shape of the manus. There are thus no grounds for suggesting that the flight of bats is notably 'better' or 'worse' than that of birds. Each has an advantage in certain aspect of performance, but in most respects their abilities and efficiency are much the same.

SUMMARY

1. A bat was trained to fly in a tilting wind tunnel. Stereoscopic photographs were taken, both by reflected and by transmitted light, and measurements of best gliding angle were made.

2. Variation of wing span and area at different speeds was much less than in birds. This is attributed to the construction of the wing, which prevents the bat from folding back the manus in flight, because this would lead to collapse of the plagiopatagium.

3. The trailing edge of the wing is normally deflected upwards in flight, at least in the distal parts. This is interpreted as providing longitudinal stability. The plagiopatagialis proprii muscles appear to act as an elevator, by deflecting the trailing edge of the plagiopatagium upwards.

4. The speed range over which the bat could glide was 5.3-11.0 meters/second. Its maximum lift coefficient was 1.5. and its best glide ratio 6.8:1. The Reynolds Number range, based on mean chord, was 3.26×10^4 to 6.79×10^4.

5. A simple regression analysis of the glide polar indicated a very high span efficiency factor (k) and low wing profile drag coefficient (C_{dp}). On the other hand, a drag analysis on the assumption that $k = 1$ leads to an improbably large increase in the estimated C_{dp} at low speeds. It is suggested that the correct interpretation probably lies between these extremes, with $k_{\sim}$ 1.5; C_{dp} would then be about 0.02 at high speeds, rising to somewhat over 0.1 at the minimum speed.

6. It would appear that the bat is not good as a pigeon at fast gliding, but better at slow-speed maneuvering. on most points of performance, however, the two are remarkably similar.

The transport of the wind tunnel from its original site at Bristol to Nairobi was financed by grants from the East African Wild Society, the Ministry of Overseas Development, and University College Nairobi (now the University of Nairobi) to all of whom I am most grateful.

I have relied heavily on the advice of my colleague Dr. F. A. Mutere for general information on bat biology, and for the selection. I am also indebted to Dr. Mutere for organizing the capture of the bats, and also to those members of the staff of the East African Virus Research Institute at Entebbe who helped with this operation. I am indebted to Drs. A. and U. M. Norberg for reading the transcript and making a number of valuable suggestions.

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"Why did he name a sophisticated flying wing sailplane after an extinct lizard that had the glide characteristics of a flower pot?"

---- Herk Stokley in his "Flying Models Magazine" Soaring column concerning Gene Dees' choice of a name for his flying wing.

---- "I'll never tell !"

Gene

The Icarosaur Flying Wing

by Gene A. Dees

The ancestry of the Icarosaur can be traced to Curt Weller's Elfe (as shown in Dan Pruss's soaring column : Model Aviation , May 1984). The reason for this is that I had originally intended to build an Elfe but, had second thoughts, since Elfe didn't incorporate the features that I had in mind for my flying wing . The only thing left of Elfe in Icarosaur is the approximate wing span of 2.6 meters (Icarosaur has, in fact, a span of 2.75 meters due to some re-engineering of the center section late in the construction phase) , the 20° leading edge sweep which I wanted anyway for reasons to be mentioned later, and the fact that Icarosaur incorporates winglets also (the Elfe's winglets are straight-up, and flat plates mounted on a wing with NO dihedral . . . Icarosaur uses an Eppler 220 and are mounted at 10° to a wing that has 3° dihedral at the center).

The total inspiration was also driven by the work of the Horten brothers in pre-World-War II Germany circa: 1930's and early 1940's. Inspiration, yes, but Icarosaur airfoils and principals resemble little of the Horten's work (but, Cripes ! Are those machines beautiful !).

The structure of Icarosaur incorporates several features that have, heretofore, been considered Bozo No-No's for flying wings . In fact, I got yelled at by an aeronautical engineer for even considering the use of an undercambered airfoil with flaps. It seems that current dogma states that if one must build a flying wing then "Thou shalt not use undercambered airfoils". . . "or flaps either !".

Besides the undercambered airfoil and flaps, the winglets (starting to appear now on commercial Biz-Jets, home-builts, and the like) use an Eppler 220. The E-220 is a "hard-to-find-the-ordinates", low Reynolds number airfoil selected since the winglets are small (9 inches long with a 5-inch root chord and a 3-inch tip chord) and they need to work at some ridiculous Reynolds numbers. The center section out to the point where the bat-tail terminates is an Eppler 174 (the aforementioned Bozo-No-No undercambered airfoil) which then begins a smooth transition out to an Eppler 184 at the tip (another weird, hard-to-find, airfoil that is reflexed in nature).

The control surfaces are humongous compared to conventional R/C sailplanes. This is a result of reading about several folks' earlier attempts at building flying wings and having the controls "blank out" during abortive spin recovery. I decided that that was not going to happen to Icarosaur . . . indeed it hasn't ! The elevons are 3.5 inches wide and 29 inches long each with the flaps being 3.5 inches by 14 inches each. Icarosaur is saved from extremely touchy control by my choice of radio equipment. I selected a

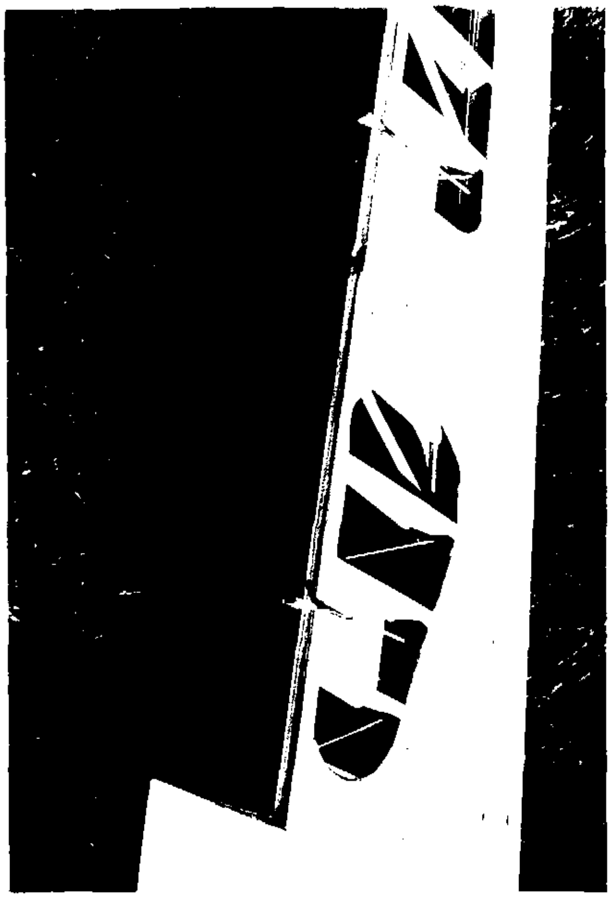
Circus Hobby JR Pattern Plane Radio for its having duel rates, elevon mixing, and reasonable price.

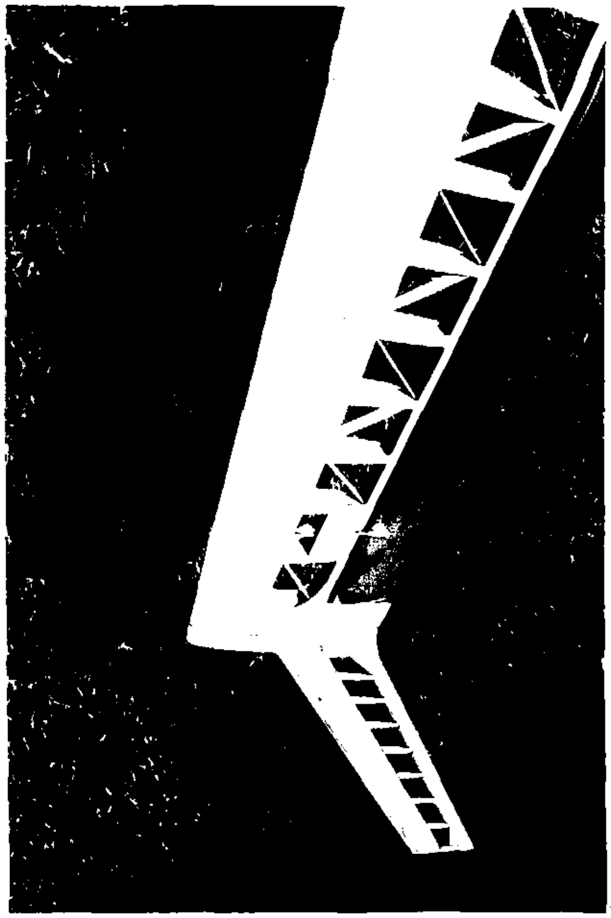
I would suggest getting the more expensive standard sized ball-bearing servos instead of the standard fare that comes with the radio since the standards sound like a basket of rattlesnakes and don't center very well. Otherwise, I'm extremely satisfied with the control placement and the fact that all the "bells and whistles" switches will not disable the controls if an extraneous switch or button is bumped. This statement needs a bit of a disclaimer . . . the long switch to right of the meter that says "FLAP" and settings for neutral, spoiler, and flap CAN DISABLE THE ELEVATOR FUNCTION of the elevons if it is bumped into the spoiler position. After this happened during an early test flight and Herk Stokely stuffed the radio under my nose while not taking his eyes off the stalling wing and saying: " What's the matter with the radio!". I reached over and flipped the offending switch back to the correct position and said: "There ! How's that?". Icarosaur then resumed normal operations. The guilty switch was, from then on, disabled by using a rubber band to the handle to hold it in the "UP" position.

The internal structure of Icarosaur seems a bit ham-handed in the "over-built" department but there is a reason for that too. I had heard and read reports of other flying wings having trouble with stability during transition from low to high speed due to flex and flutter. Icarosaur was not going to flutter and flex if I had any say in the matter . . . besides, the old saying goes; "Prototypes are ALWAYS HEAVIER than the production models.". The spars are the same size spruce that some folks use in 4 meter models (3/4" by 1/8" with 3/8 inch shear webs . . . 1/2 inch webs in the center section with medium fiberglassing out to the point where the secondary spar (same size as the main spar) joins the main. So, what the heck, I didn't really care how much the beast weighed.

Well, I started caring when I found out Icarosaur weighed in at 5-1/4 pounds and was surprised that the weight was just right. As heavy as Icarosaur is, it appears that she needs it with the speeds at which she is capable.

The plans for Icarosaur are drawn with detachable wing-tips and though the prototype is a one-piece construction job (I bought a Dodge Caravan mid-way through the building phase and can carry the wing conveniently as a one-piece). I realize that a lot of folks that build one in the future may own a VW Beetle or a Honda. Thus, that option is available although, after flying Icarosaur, I would strongly recommend the one-piece version . . . I've been told that I have "concrete feet" when it comes to zoom-launches and have pushed the poor bird to the point that Herk flinches every time I zoom. So far, I'm not too worried and the Icarosaur joke going around (started by folks that saw the plane before it was covered) was that if it didn't fly worth a hoot then I could install a fixture for a mast and use it as a weird





windsurfer . . . or take it down to the swimming hole and use it as a diving board !

The winglets (detachable in the plans AND on the prototype) are similarly "over-built" to prevent flutter and destruction during ground loops. I did that once while landing on a windy day and the beast came to rest, inverted, on its nose and winglets . . . no damage ! The structure consists of 1/4 by 1/8 inch spruce spars upper and lower and D-tube sheeted with, of all things, 1/64 inch ply ! The winglet ribs are even laminated with 1/64 inch ply!

All this "tonnage" at the tips (analogous to the tail on a conventional sailplane) translates to some lead in the nose weight bays . That arrangement helps considerably in bringing the flying weight up to 5-1/4 pounds so I figured that if I needed to shed some weight, lighter winglets would do it since I could then shed considerable amounts of lead from the nose. Well, that move wasn't necessary and the old saying; "If it works, don't fix it !" applies. Icarosaur flies quite nicely the way she is.

The 20° wing joiner presented a problem in how to build it without making it a real pain to fabricate. I asked Bob Champine, an old free-flight flyer, how to put a permanent bend in spruce and he said to soak it in household ammonia for a day, then bend to the desired angle, pin in place and leave to dry thoroughly. Four pieces of 3/4 by 1/8 inch spruce were soaked and the four pieces stacked and bent together. After drying, they were laminated with Super-T. Just try to break that joiner with your hands! All you'll get for your trouble are cut hands and a hernia. If the wing ever does break during a "muscle-zoom", I can guarantee that it won't break in the center ! The secondary spar joiner also uses a "4-ply" spruce joiner, however, this one doesn't need bending.

Launching Icarosaur is a mite different than a conventional job in that it uses twin-towhooks . . . I had heard war stories about adverse yaw in flying wings and wanted to eliminate as much of that as possible from the beginning. The nylon yoke was tied in the center on the first flights and the launches were real "gut-wrenchers"! After several coronaries, I tried not tying the yoke in the center and letting it slip free through a ring attached to the launch line above the parachute. This idea was not mine (I wish it was). I had read about it in one of Ken Bates' papers about launching flying wings and it makes all the difference in the world for, now, Icarosaur is VERY STABLE during launch . . . as a testimony, I can now launch it without an experienced pilot (Herk) to help me out of jams. You see, Icarosaur is only the fourth plane that I have ever built and the first plane that I have ever designed. It is also the first plane that I have ever flown that had aileron-type controls . . . so I'm not all that experienced in flying different types of sailplanes . I went clear through level IV with a Craftaire Drifter II and a stock Paragon and now that the launch problems with Icarosaur have been solved, I'm comfortable flying the "wing".

Flying Icarosaur is just like flying a fast aileron ship with no surprises. The speed Icarosaur is capable of has not yet been fully explored. You can get surprising speed out of her by reflexing flaps or just dipping the nose a little. Icarosaur has flown where ever I have wanted it to go in 25 knot winds and Herk did a speed run with it during a contest that had the F3B freaks suddenly wanting a set of plans. I assume that that is good since I have to take their word for it since I have never seen F3B flown much less done it myself . . . I am, at present, a thermal flyer of the southern USA variety complete with red, sunburned neck !

The flaps work with no more down-pitch than spoilers and help a heck of a lot on landing. One important difference to remember . . . RETRACT THOSE BIG FLAPS THE INSTANT BEFORE LANDING since they are big enough to drag the ground and can be damaged on landing.

For those who are used to "dorking" in order to get that 100-point landing: Don't do it with Icarosaur ! The keel is designed to take stress off the wing during rough landings but has the effect of causing the plane to "ricochet" after the attempted "dork" and you find yourself 6 feet in the air again with no hope of regaining the spot. A timing belt glued to the bottom of the keel may help this but, I have found a change in approach tactics to work just as well. The keel, by the way, is made from 4 sheets of 3/8 inch balsa laminated with 1/64 inch ply and sanded to shape, then heavily fiberglassed all around. Then the keel is glued to the bottom center of the wing with silicon rubber glue . . . all this after the wing itself has been sanded and fiberglassed (finished except for covering). This contraption has held up through rough landings on concrete and gravel with only scratched paint to show for all of it.

A 3-sheet set of rolled plans are available for the "Icarosaur" Flying Wing. There are 1:1 scale sheets for each wing-half and one separate sheet for rib templates as there are 38 rib templates ranging in size from the center bat-tail rib (19-2/3") to the winglet tip rib (approx. 2-1/2")! Also included is an instruction booklet that includes directions for making the foam building bed necessary for construction of the variable airfoil wing.

The "Icarosaur" plan set cost $20.00 for the continental U.S. and $35.00 for overseas. The plans are shipped in a heavy mailing tube and the cost is not cheap for overseas mailing. My address is on the "contents" page.

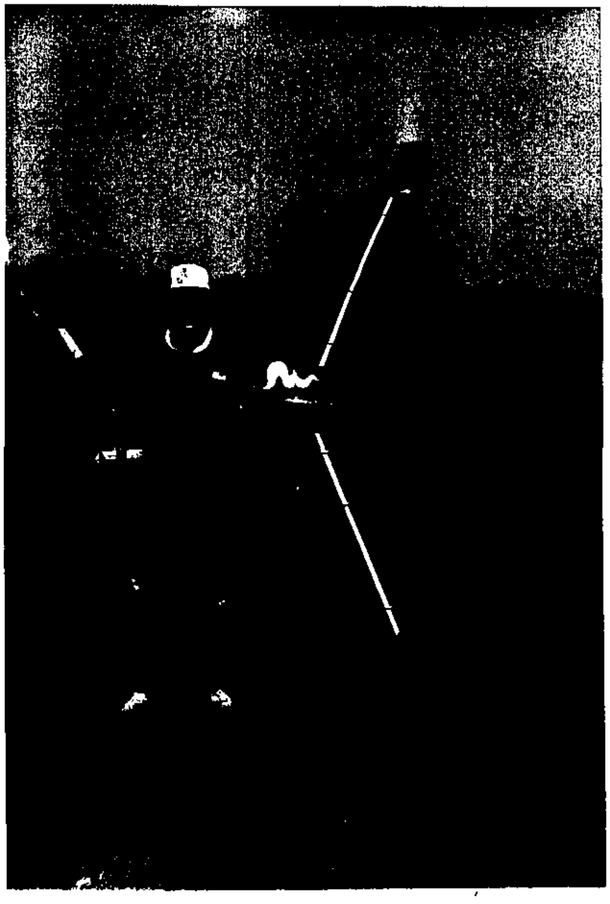
Mark Kummerow's "Ultrasaur"

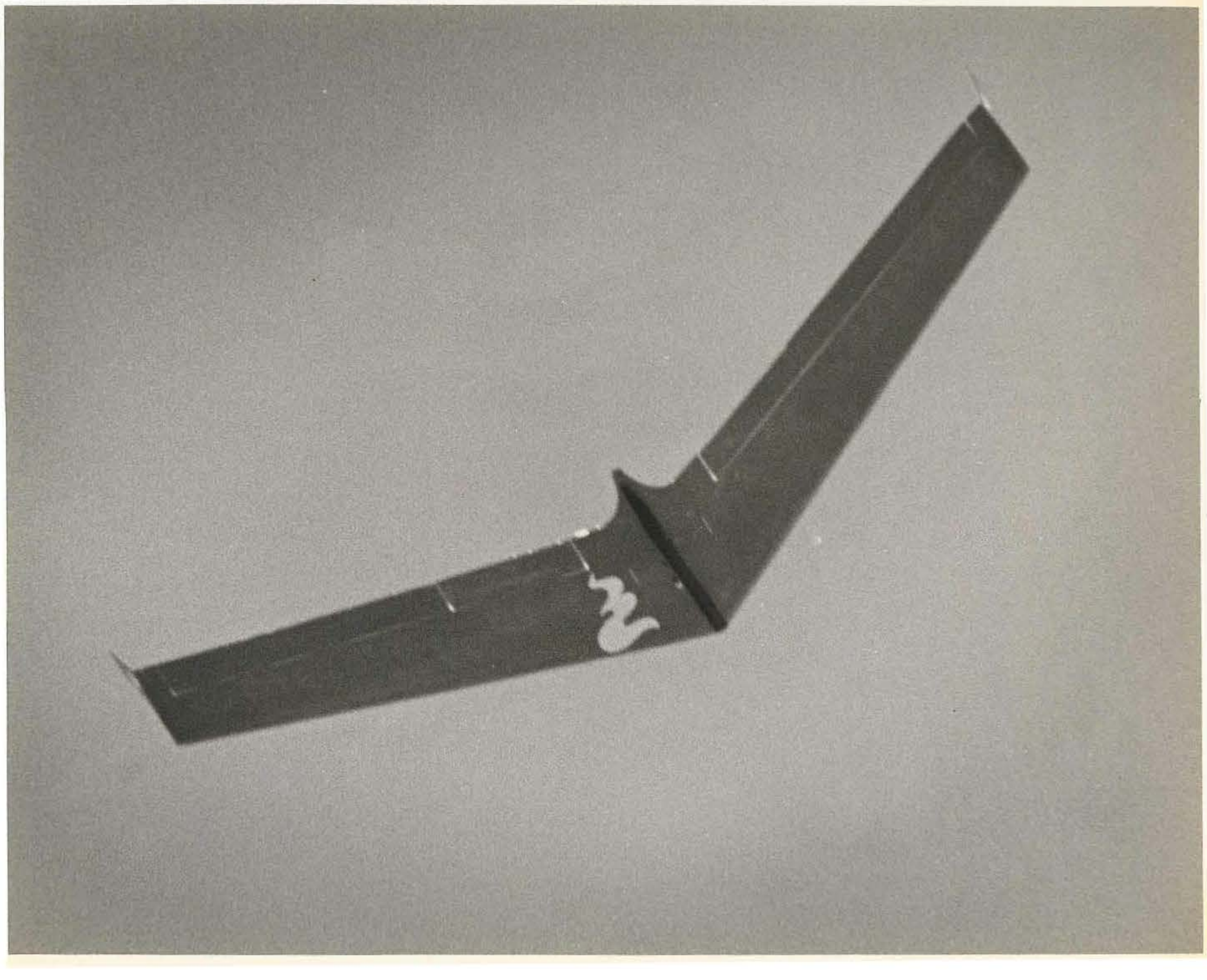
During the production of Soar Tech VII, word was received concerning the completion and display of Mark Kummerow's 16.7 foot "Ultrasaur" at the Toledo Show. Mark won first place in the Sport Sailplane category at Toledo and a photo of Mark with his "Ultrasaur" appeared in the July issue of Model Aviation Magazine.

A number of months back Mark called to tell of the demise of his big 16-foot V-tail. He wanted to replace it with some "unique" and asked for a set of "Icarosaur" plans. He had in mind to keep the bat-tail and tip dimensions while increasing the aspect ratio "a bit". I sent the plans ASAP while Herk plotted the ribs via his modified Chuck Anderson plotting program. The Eppler 174 bat-tail ribs were increased to 13% thick to allow for a stronger structure to accomodate the intended 16.7-foot span. From flight tests of "Icarosaur" it was determined that a 10% thick Quabeck airfoil at the tip would work nicely on a beast this size. The winglets were extended to 14 inches likewise to accomodate the size of "Ultrasaur".

Well, the plans were sent along with the rib plots and the next we heard of the project was when Mark won with it at Toledo!

The specifications for "Ultrasaur" are as follows: 16.7 foot span, 12 pounds, 20° sweep, 11-7/8 inch average chord, 2500 sq. inches, 13% thick Eppler 174 bat-tail section, 10% Quabeck wingtip airfoil, 5° washout, 6° dihedral, NACA 0009 winglet airfoil,14 inch winglet span (each).





"Something that beautiful
just has to be built !"

---- Herk Stokely

CG Location and Variable Airfoils for Flying Wings

Location of the CG on a Flying Wing can be somewhat of a problem since it is hard to consult the "local expert" in your flying club when very few folks have experience with Flying Wings! I had this problem constantly while designing and building Icarosaur. The CG for Icarosaur was first figured the hard way. That is; fiddling, figuring, measuring, and testing with an aeronautical engineer (Herk Stokely) initially figuring mechanically by way of neutral points.

Since then, a nifty little computer program has come my way that does the job a lot faster and more accurately. Icarosaur's CG as arrived at by much trial and tribulation was checked against the program's output with only 1/16 inch difference! It would have saved a lot of hassle if I had the program in the beginning!

The program was originally written by Dick Sarpolus and published in Soar Tech 2 .Some modifications to allow figuring complex wings were added later by Herk Stokely to put it in its present form. The program was meant for conventional aircraft and works well for Flying Wings if you remember to input low values (.01) for all dimensions concerning the fuselage and tail.

This program is written in Basic and ran nicely on Herk's KayPro. He sent it to me via modem and it ran fine with no modifications on my Macintosh-Plus using Microsoft Basic. I figure that it will run on just about any machine that can run Basic since there are no "funny" codes peculiar an any particular machine written into it. To run it, just type in the information it asks for at the prompts.

The variable airfoil wing used on Icarosaur was developed with the aid of a modified version of Chuck Anderson's Airfoil Plot program. Herk Stokely modified Chuck's original program to allow transition from one airfoil to another entirely different airfoil with each plotted rib being a little different from the preceeding one. Those interested in this airfoil plotting program can obtain a copy from Chuck Anderson for $25 . . . . . you should inquire first to see if he has a version for your machine. The last time I checked, Chuck had versions for Commodore, IBM, Apple II series, and Apple Macintosh.

The following program calculates the CG for aircraft and displays the results on the screen. For calculating the CG on a Flying Wing, remember to input low values (.01) for the fuselage and the tail.

```
10 DIM A$(8), B$(9)
11 G5=0
15 PRINT CHR$(26)
20 PRINT
30 PRINT
40 PRINT
50 PRINT
60 PRINT
70 PRINT "INPUT DATA IN ANY CONSISTENT SYSTEM OF UNITS"
71 PRINT "DEFINE A SIMPLE WING WITH STRAIGHT TAPER AND SWEEP"
72 PRINT "OR A COMPLEX WING WITH AREAS OF DIFFERENT TAPER AND"
74 INPUT "SWEEP.  DO YOU WISH SIMPLE OR COMPLEX (S OR C)";C$
76 IF C$="C" THEN 1440
80 PRINT
90 INPUT "TOTAL WINGSPAN=?";B4
100 REM
110 INPUT "WING ROOT CHORD=?";R1
120 REM
130 INPUT "WING TIP CHORD=?";T1
140 REM
150 INPUT "WING L.E. SWEEP IN UNITS(FORWARD=-X)=?";D1
160 REM
170 INPUT "TOTAL SPAN OF HORIZ STAB=?";B5
180 REM
190 INPUT "HORIZ STAB ROOT CHORD=?";R2
200 REM
210 INPUT "HORIZ STAB TIP CHORD=?";T2
220 REM
230 INPUT "HORIZ STAB L.E. SWEEP (FORWARD= -X)=?";D2
240 REM
250 INPUT "NUMBER OF VERTICAL FINS=?";V2
260 REM
270 IF V2=0 THEN 380
280 INPUT "VERTICAL FIN HEIGHT=?";B3
290 REM
300 INPUT "VERT FIN ROOT CHORD=?";R3
310 REM
320 INPUT "VERT FIN TIP CHORD=?";T3
330 REM
340 INPUT "FIN L. E. SWEEP (FWD=-)=?";D3
350 REM
360 INPUT "FIN OFFSET FROM WING L.E.";L3
370 REM
380 INPUT "ENTER 2 FOR CANARD, 1 FOR OTHER";C
390 REM
400 INPUT "DISTANCE BETWEEN WING AND STAB AT ROOTS=?";L1
410 REM
420 B1=B4/2
430 B2=B5/2
440 X1=((R1^2+R1*T1+T1^2)/(R1+T1)/6)+(D1/3*(R1+2*T1)/(R1+T1))
442 IF G5=1 THEN X1=G4
450 X2=((R2^2+R2*T2+T2^2)/(R2+T2)/6)+(D2/3*(R2+2*T2)/(R2+T2))
```

```
460 IF V2=0 THEN 480
470 X3=((R3^2+R3*T3+T3^2)/(R3+T3)/6)+(D3/3*(R3+2*T3)/(R3+T3))
480 S1=B1/2*(R1+T1)
482 IF G5=1 THEN S1=A1
490 S2=B2/2*(R2+T2)
500 IF V2=0 THEN 520
510 SF=B3/2*(R3+T3)
520 L=X1-X2+L1+R2
530 IF C=1 THEN 570
540 P=((L*S2)/S1)-((R1^2+R1*T1+T1^2)/(15*(T1+R1)))
550 IF V2=0 THEN 610
560 GOTO 580
570 P=((L*S2)/(3*S1))-((R1^2+R1*T1+T1^2)/(15*(T1+R1)))
580 F=P+L3+X3-X1
590 IF V2=0 THEN 610
600 V=3*B1*S1/(100*F*SF)
610 PRINT
620 PRINT TAB(20);"INPUT DATA"
630 PRINT TAB(20);"===== ===="
640 PRINT
650 PRINT "MAIN WING DIMENSIONS IN UNITS"
660 PRINT "---- ---- ---------- -- ------"
670 PRINT "TOTAL SPAN = ";B4
672 IF G5=1 GOTO 1650
680 PRINT "WING ROOT CHORD = ";R1
690 PRINT "WING TIP CHORD = ";T1
700 PRINT "WING ROOT/TIP OFFSET = ";D1
710 PRINT
720 PRINT "HORIZONTAL STAB. DIMENSIONS IN UNITS"
730 PRINT "---------- ----- ---------- -- ------"
740 PRINT "TOTAL SPAN = ";B5
750 PRINT "ROOT CHORD = ";R2
760 PRINT "TIP CHORD = ";T2
770 PRINT "LE ROOT/TIP OFFSET = ";D2
780 PRINT "LENGTH OF FUSE BETWEEN WING & STAB = ";L1
790 PRINT
800 IF V2=0 THEN 920
810 PRINT "VERT. FIN DIMENSIONS IN UNITS"
820 PRINT "----- --- ---------- -- ------"
830 IF V2=1 THEN 860
840 PRINT "THERE ARE TWO VERTICAL FINS"
850 GOTO 870
860 PRINT "THERE IS ONLY ONE VERTICAL FIN"
870 PRINT "FIN HEIGHT = ";B3
880 PRINT "FIN ROOT CHORD = ";R3
890 PRINT "FIN TIP CHORD = ";T3
900 PRINT "FIN LE ROOT/TIP OFFSET = ";D3
910 PRINT "FIN LE OFFSET FROM WING LE = ";L3
920 PRINT
930 INPUT "HIT RETURN TO CONTINUE";QQ
940 PRINT TAB(20)"OUTPUT DATA"
950 PRINT TAB(20)"====== ===="
960 PRINT
970 PRINT "AIRFOIL SHADOW AREAS IN SQUARE UNITS"
```

```
980 PRINT "TOTAL WING AREA = ";(2*S1)
990 PRINT "TOTAL STAB AREA = ";(2*S2)
1000 IF V2=0 THEN 1020
1010 PRINT "TOTAL VERTICAL FIN = ";(V2*SF)
1020 PRINT
1030 REM
1040 PRINT "AERODYNAMIC CENTERS OF SURFACES (UNITS AFT OF L.E. AT
FUSE)"
1050 PRINT "WING A.C. = ";X1
1060 PRINT "HORIZ STB A.C. = ";X2
1070 IF V2=0 THEN 1090
1080 PRINT "VERTICAL FIN A.C. = ";X3
1090 PRINT
1100 PRINT
1110 IF C=1 THEN 1140
1120 PRINT "CANARD DESIGN C.G. IS ";(P-X1);"UNITS AHEAD OF WING LE AT
FUSE"
1130 GOTO 1150
1140 PRINT "CONVENTIONAL DESIGN C.G. IS ";(P+X1);" UNITS BEHIND WING
LE AT FUS"
1150 PRINT
1160 IF (C=1) OR (V2=0) THEN STOP
1170 PRINT "THE VEE EQUATION YIELDS ";V
1180 PRINT
1190 IF V2=1 THEN 1230
1200 S6=3*B1*S1/(100*F)
1210 F6=3*B1*S1/(100*SF)
1220 GOTO 1250
1230 S6=3*B1*S1/(50*F)
1240 F6=3*B1*S1/(50*SF)
1250 P9=SF/S6*100
1260 IF P9 >= 100 THEN 1290
1270 A$="SMALLER"
1280 GOTO 1300
1290 A$="LARGER"
1300 L9=F6-P+X1-X3
1310 IF L9 >= 0 THEN 1340
1320 B$="AHEAD OF"
1330 GOTO 1350
1340 B$="BEHIND"
1350 PRINT "VERTICAL FIN AREA IS ";A$;" THAN NEEDED. OPTIMUM AREA
SHOULD BE"
1360 PRINT (100*S6/SF);" % OF PRESENT DESIGN OR ";S6;"SQUARE UNITS."
1370 PRINT "FOLLOWING IS A SUGGESTED DESIGN MODIFICATION:"
1380 PRINT "FIN ROOT CHORD = ";R3
1390 PRINT "FIN TIP CHORD = ";T3
1400 PRINT "FIN LE SWEEP = ";D3
1410 PRINT "FIN HEIGHT = ";(B3/P9*200)
1420 PRINT "NEW DIMENSIONS YIELD AREA OF ";(B3/P9*50*(R3+T3));"
SQUARE UNITS"
1425 INPUT P$
1430 PRINT
1440 PRINT "UP TO THREE SECTIONS MAY BE ENTERED. IF LESS ENTER 0'S"
1450 INPUT "TOTAL WING SPAN = ";B4
```

```
1460 INPUT "ROOT CHORD = ";K0
1470 INPUT "SPAN TO FIRST BREAK = ";S3
1480 INPUT "CHORD AT FIRST BREAK = ";K1
1490 INPUT "LE SWEEP AT FIRST BREAK (- IF FWD) = ";P1
1500 INPUT "DELTA SPAN TO SECOND BREAK = ";S4
1510 INPUT "CHORD AT SECOND BREAK = ";K2
1520 INPUT "LE SWEEP AT SECOND BREAK (- IF FWD) = ";P2
1530 INPUT "DELTA SPAN TO TIP = ";S5
1540 INPUT "TIP CHORD = ";K3
1550 INPUT "LE SWEEP AT TIP (- FWD) = ";P3
1560 A1=(S3*(K0+K1)/2+S4*(K1+K2)/2+S5*(K2+K3)/2)
1570 G1=((K0+2*K1)*P1+.5*(K0^2+K0*K1+K1^2))/(3*(K0+K1))
1580 G2=((K1+2*K2)*(P2-P1)+.5*(K1^2+K1*K2+K2^2))/(3*(K1+K2))+P1
1590 G3=((K2+2*K3)*(P3-P2)+.5*(K2^2+K2*K3+K3^2))/(3*(K2+K3))+P3
1600 G4=(G1*S3*(K0+K1)+G2*S4*(K1+K2)+G3*S5*(K2+K3))/(2*A1)
1610 R1=K0
1620 G5=1
1640 GOTO 160
1650 PRINT "WING GEOMETRY VALUES ARE:"
1660 PRINT "CHORDS    DELTA SPANS    SWEEPS"
1670 PRINT K0;"          ";S3;"          ";P1
1680 PRINT K1;"          ";S4;"          ";P2
1690 PRINT K2;"          ";S5;"          ";P3
1700 PRINT "TIP CHORD = ";K3
1710 GOTO 710
```

The above program is yours gratis, courtesy of Dick Sarpolus and Herk Stokely.

A copy of Chuck Anderson's Airfoil Plot Program may be obtained for $25 from:

CHUCK ANDERSON
PO BOX 305
TULLAHOMA, TN 37388

State which type of computer : Commodore, IBM, Apple-series, or Apple Macintosh. Inquire as to what others are available.

- Gene Dees

"There are days when I just feel like taking the wing out and bombing somebody, besides, it's the only time I get to wear my Darth Vader helmet."

---- The Lightning Bug

---- from the underground cult classic movie **J-Men Forever**

Dave Jones asked Michael Selig a while back if he would design some airfoils for flying wings . . . and if he would, could they be put in Soar Tech. Well, Michael did and I did.

So . . . here they are !

Gene Dees
editor Soar Tech VII

The

S5010-098-86

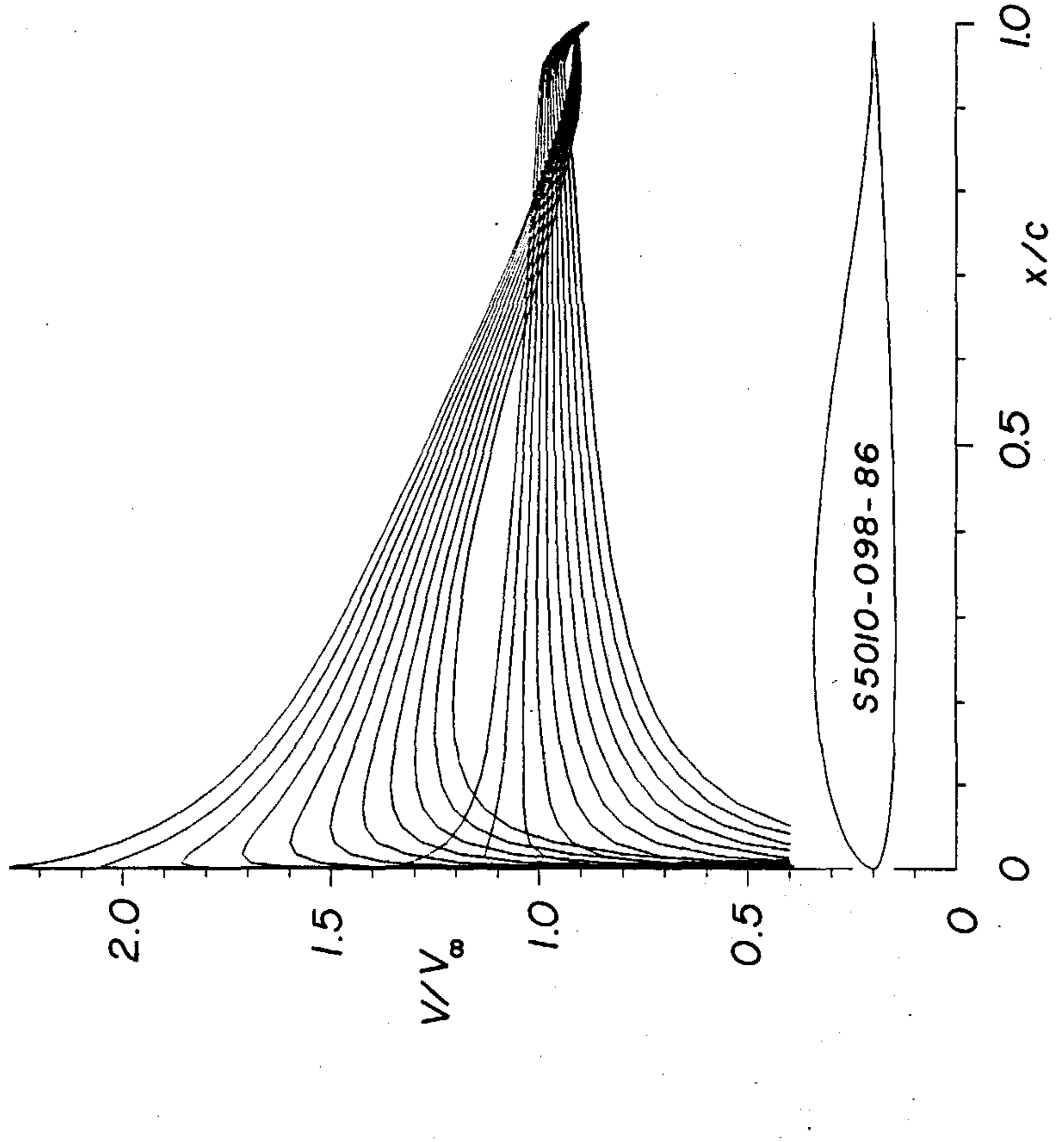
and

S5020-084-86

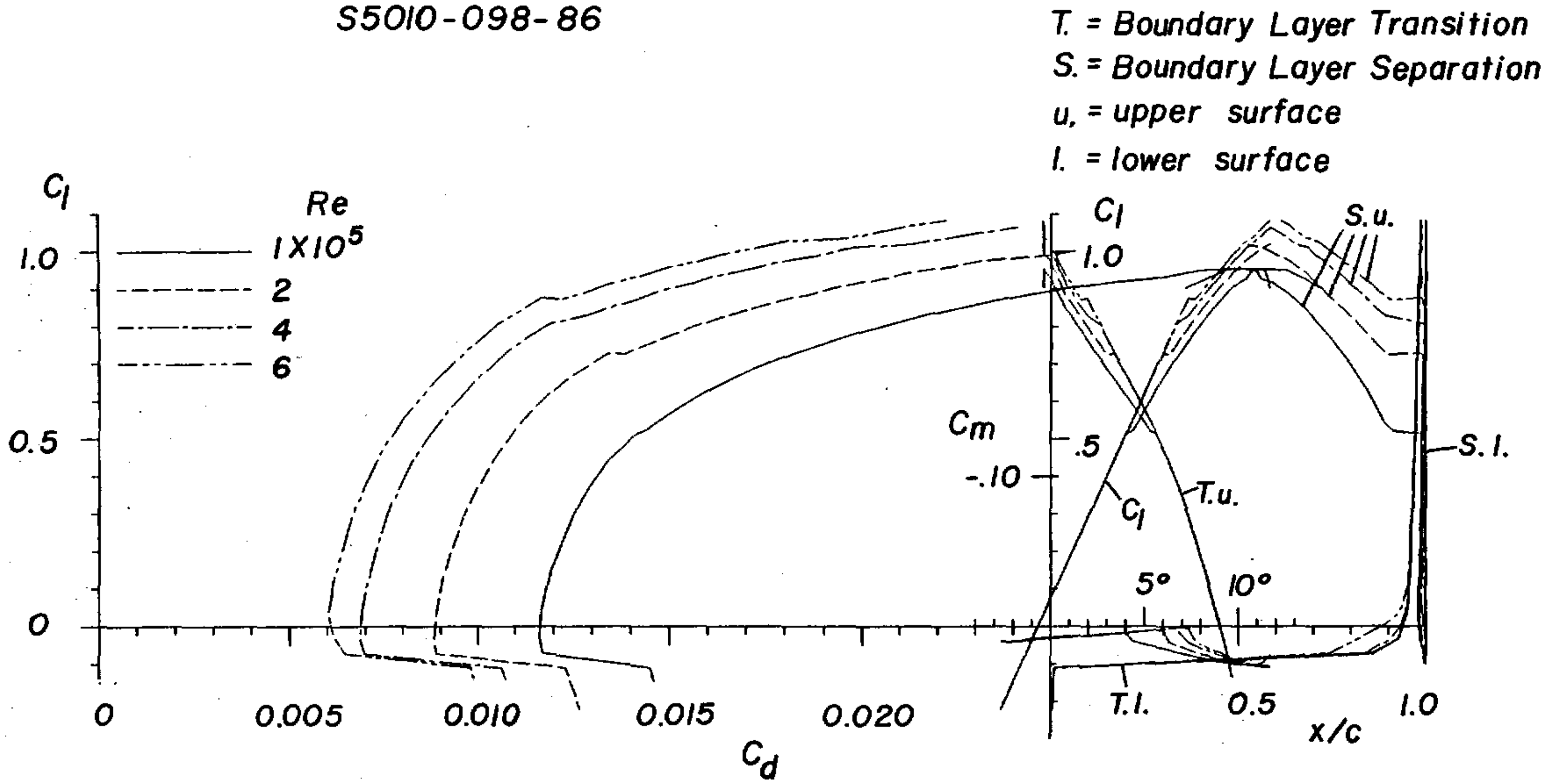
Flying Wing Airfoils

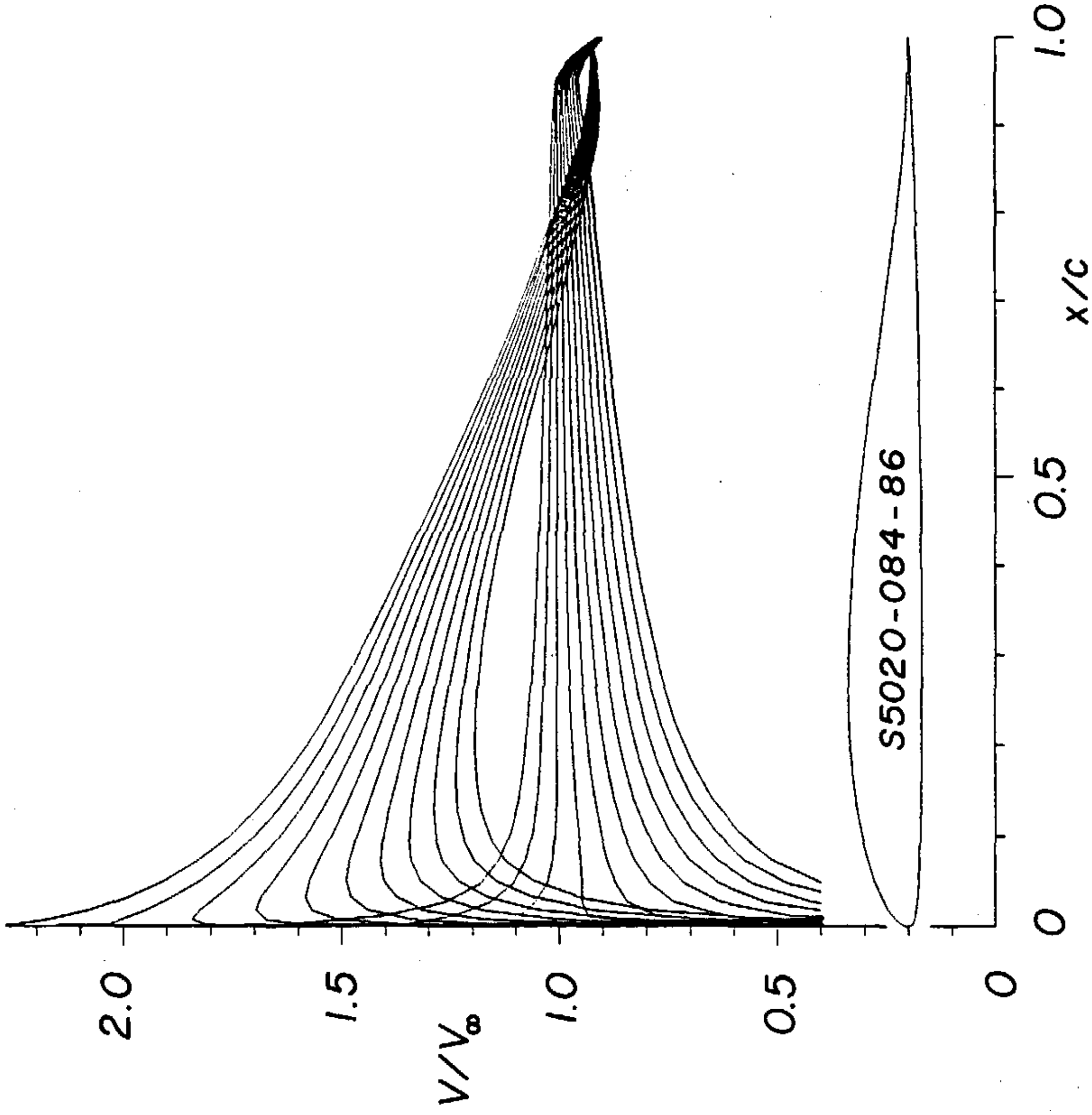
designed by Michael Selig

8-16-86



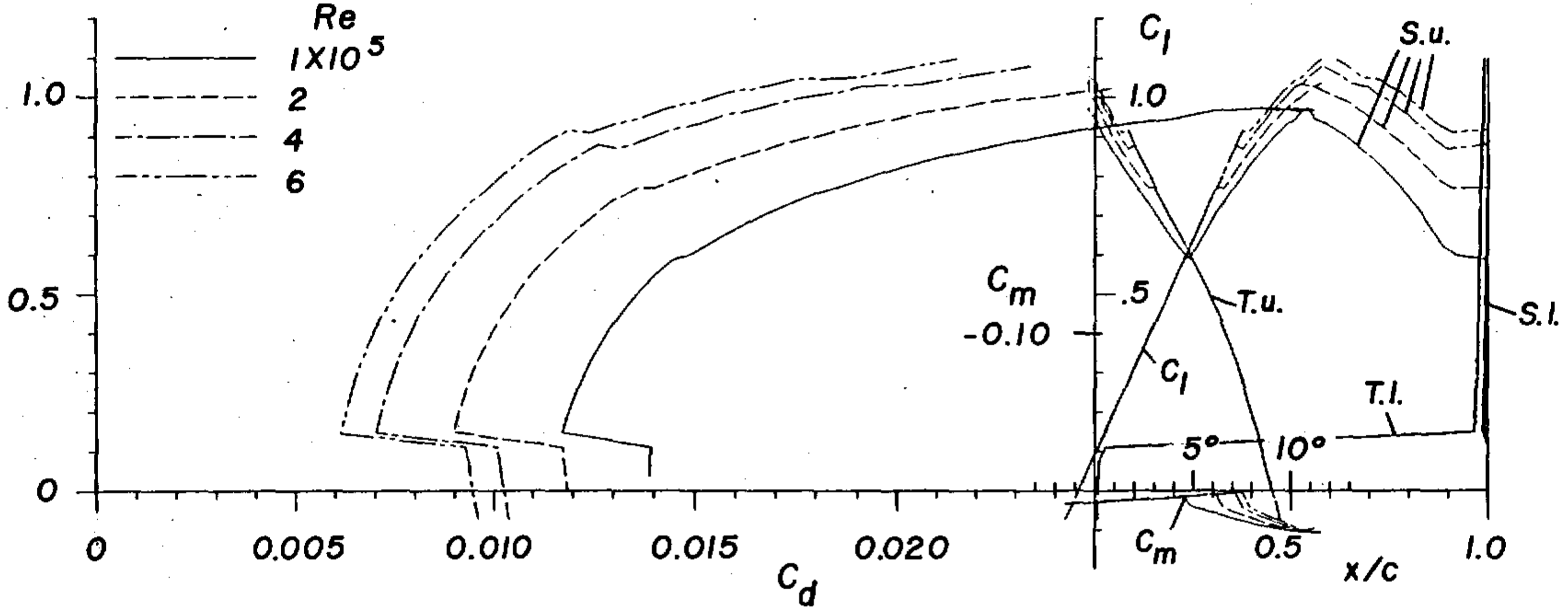
S5010-098-86


T. = Boundary Layer Transition
S. = Boundary Layer Separation
u, = upper surface
l. = lower surface
C_l
Re
1X10^5
2
4
6
1.0
0.5
0
0
0.005
0.010
0.015
0.020
C_d
C_l
1.0
C_m
.5
-.10
C_l
T.u.
S.u.
S.l.
5°
10°
T.l.
0.5
1.0
x/c


2.0
1.5
1.0
0.5
0
V/V∞
0
0.5
1.0
x/c
S5020-084-86

S5020-084-86

T. = Boundary Layer Transition
S. = Boundary Layer Separation
u. = upper surface
l. = lower surface



AIRFOIL S5020-084

N	X	Y
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3	0.97160	0.00015
4	0.94964	0.00066
5	0.92171	0.00186
6	0.88833	0.00413
7	0.85028	0.00766
8	0.80840	0.01234
9	0.76339	0.01795
10	0.71594	0.02430
11	0.66672	0.03116
12	0.61644	0.03827
13	0.56576	0.04524
14	0.51519	0.05170
15	0.46516	0.05736
16	0.41608	0.06198
17	0.36830	0.06539
18	0.32218	0.06748
19	0.27803	0.06821
20	0.23620	0.06759
21	0.19702	0.06565
22	0.16081	0.06244
23	0.12785	0.05802
24	0.09837	0.05249
25	0.07257	0.04596
26	0.05059	0.03862
27	0.03252	0.03065
28	0.01843	0.02234
29	0.00833	0.01401
30	0.00219	0.00613
31	0.00002	-0.00049
32	0.00308	-0.00507
33	0.01226	-0.00815
34	0.02727	-0.01037
35	0.04807	-0.01192
36	0.07434	-0.01310
37	0.10563	-0.01404
38	0.14148	-0.01478
39	0.18141	-0.01534
40	0.22491	-0.01569
41	0.27150	-0.01583
42	0.32064	-0.01576
43	0.37179	-0.01550
44	0.42436	-0.01507
45	0.47776	-0.01449
46	0.53139	-0.01379
47	0.58462	-0.01297
48	0.63687	-0.01206
49	0.68752	-0.01108
50	0.73601	-0.01004
51	0.78178	-0.00896
52	0.82430	-0.00785
53	0.86308	-0.00672
54	0.89767	-0.00557
55	0.92767	-0.00440
56	0.95276	-0.00317
57	0.97279	-0.00188
58	0.98763	-0.00079
59	0.99686	-0.00018
60	1.00001	-0.00000

ALPHAO = 0.82 DEGREES   CMO = 0.0084   ETA = 1.068

AIRFOIL S5010-098

N	X	Y
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1	0.99676	0.00001
2	0.98707	0.00007
3	0.97101	0.00036
4	0.94870	0.00108
5	0.92041	0.00256
6	0.88667	0.00516
7	0.84828	0.00903
8	0.80608	0.01406
9	0.76076	0.02008
10	0.71307	0.02688
11	0.66377	0.03420
12	0.61355	0.04163
13	0.56296	0.04877
14	0.51247	0.05529
15	0.46251	0.06093
16	0.41348	0.06546
17	0.36576	0.06873
18	0.31969	0.07063
19	0.27560	0.07113
20	0.23383	0.07023
21	0.19473	0.06799
22	0.15860	0.06445
23	0.12573	0.05968
24	0.09637	0.05377
25	0.07071	0.04688
26	0.04889	0.03915
27	0.03102	0.03081
28	0.01718	0.02214
29	0.00739	0.01348
30	0.00167	0.00533
31	0.00015	-0.00140
32	0.00424	-0.00650
33	0.01456	-0.01084
34	0.03028	-0.01471
35	0.05123	-0.01804
36	0.07718	-0.02082
37	0.10785	-0.02306
38	0.14291	-0.02481
39	0.18194	-0.02609
40	0.22448	-0.02688
41	0.27008	-0.02715
42	0.31829	-0.02691
43	0.36864	-0.02623
44	0.42055	-0.02517
45	0.47345	-0.02381
46	0.52675	-0.02219
47	0.57983	-0.02039
48	0.63209	-0.01846
49	0.68292	-0.01645
50	0.73173	-0.01443
51	0.77792	-0.01243
52	0.82095	-0.01049
53	0.86030	-0.00865
54	0.89547	-0.00691
55	0.92603	-0.00527
56	0.95163	-0.00367
57	0.97211	-0.00212
58	0.98730	-0.00088
59	0.99678	-0.00019
60	1.00001	-0.00000

ALPHAO = 0.64 DEGREES   CMO = 0.0086   ETA = 1.076

"Well I'll be damned! It flies !"

---- Gene Dees (Labor Day 1985)

An Electric, Modified "Standard Plank"

by Robert A. Thornburg

The Standard Plank was created by Chuck Clemans and Dave Jones. The plans and construction article were published in the July 1975 issue of R/C Modeler magazine.

I was impressed by the simplicity of the design and especially the low wing loading. At the time " the lighter-the-better" was the prevailing philosophy of R/C Soaring and 4 oz./ft^2 was great ! The bird was easy to build except that it took FOREVER to put top and bottom rib capstrips on 32 thin (1/16") ribs using contact cement (these were the days before cyanoacrylate glues) !

The airfoil is described as being derived from a reflexed version of the NACA 6409 (Olympic 99, etc.) called a CJ-2 airfoil. Controls are rudder and elevator. The wing is two piece with plug-in tips, an area of 1090 in^2, and an aspect ratio of 10:1. The wingspan is 100 inches (thus the "standard" in "Standard Plank"). The dihedral angle is 6° each tip.

The Standard Plank was covered in Solarfilm as it was the local favorite and was less expensive and easier to work with than Monokote. This was a good choice as it is still on there after 12 years ! I finished it in blue (leading edge sheeting), transparent red (open rib areas), and white (elevators and trailing edge). Its first flights were in 1976. After trimming out with hand launches, I put it on a high start for the wildest launch I have ever seen. The Standard Plank heeled over to the right and went almost parallel to the ground before the rudder took effect and then heeled over to the left ! These wild occilations gradually dampened as the launch flattened out. Launches were always low (but always exciting!). I finally realized that at steep launch angles the full flying rudder was being blanked out of the airflow by the wing! I built a much taller and deeper rudder and launches improved considerably. The launches were not as high as conventional sailplanes, though.

I made a removable nose that allowed me to replace it with a TeeDee for higher altitudes and some good flights. The TeeDee did make a mess on the plane and was soon retired.

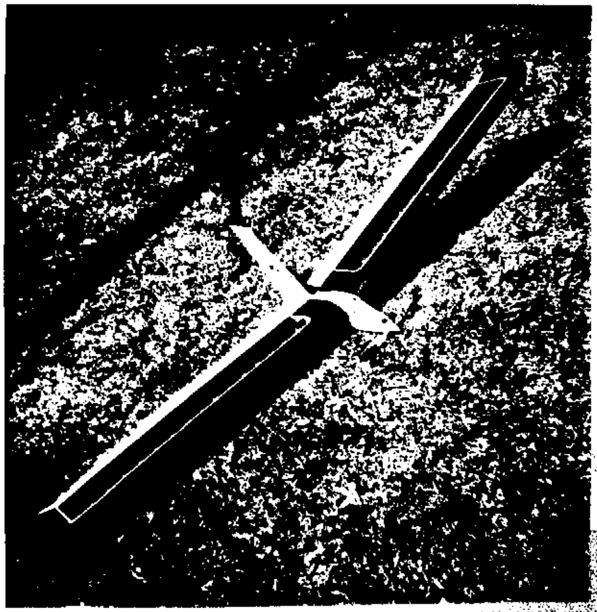
The Standard Plank looked like a great patriotic hawk in the air, but was never a consistent performer. It had a constant porpoising flight path that could not be trimmed out. It also had a high sink rate. It often spent long periods on the shelf (in the bi-centennial year of 1976 it hung in the local hobby shop for the month of July).

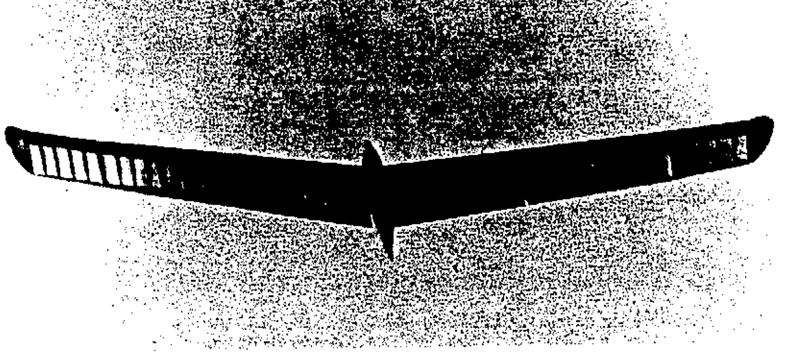
In 1985 I was talking long distance to Gene Dees, and he told me about this great new electric motor that Woody Blanchard was experimenting with called a Graupner Jumbo. I immediately thought of the Standard Plank (no longer "Standard" as it now sported wing tip extensions for a total of 10 feet). I installed one and have been very pleased. The motor with folding prop and 10 800 mah batteries added 10 oz. to the flying weight. Total weight was now 64 oz.

The climb under power is respectable, with 400-500 foot launches with approximately 1 minute motor runs. The big surprise was that it now soars without the porpoising and has a much lower sink rate! Apparently the low wing loading caused it to 'mush' a lot. I now fly Standard Plank (without the long tips that cause too much drag on launch and reduce maneuverability) more than anything I own. It attracts a lot of attention and is fun to fly. It holds its own against the new high tech airfoils and soars in the tightest of thermals. Penetration is good. It sure is nice to get way downwind or in a tight spot on landing and then be able to fire up again!

Alas, I have run into some misfortune with it. I was flying at about 1000+ feet and decided to come down to help someone else fly, and decided to try descending inverted. The wing developed incredible flutter and acted oddly for the rest of the descent after rolling out. When about 10 feet from the ground, it suddenly started a left circle and wouldn't straighten out. I called out those four infamous words: "I don't have it!", and everyone watched in morbid fascination as that beautiful bird homed in on 'B' light pole† . It hit at about 30 mph and about six feet up. Pieces flew everywhere! We were amazed to find the wing still intact (one small area of crushed sheeting) but the gearbox and prop assembly were totaled! The motor suffered some bent metal but still works. The gear shaft was bent into a 'U'. The fuselage was also totaled forward of the wing. The high current drain ran down the battery, which had about 90 minutes on it that day (the Rx Battery, not the engine battery--Ed.).

A new motor and gear assembly has been ordered. In the mean time, I am back to flying the plank as a pure sailplane (27 minute flight last Sunday).††





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† Editor's Note: The flying field mentioned by Bob Thornburg is a grass field that serves as a parking lot for North Carolina State University's Carter-Finley Stadium and sports cement light poles with large signs with letters on them to aid fans in finding their cars after football games. Visitors to the Raleigh Independent Soaring Enthusiests' (R.I.S.E.) flying site often feel as though the field would be well suited for plyon races and each pole has claimed its share of mis-guided sailplanes over the years !

†† It has been some time since Bob wrote this article and I'm happy to report that his vererable old electric plank is back in all its former glory! --- Gene

061-487 1704

223 Bramhall Moor Lane
Hazel Grove
Stockport SK7 5JL

6th May, 1987

Gene A Dees, 2309-B Walke Street, Virginia Beach, VA 23451, USA

Dear Gene,

I thought you might like the enclosed photo for the flying wing Soartech - pass it on to Herk if I'm too late. It is - at last! - the definitive MERLIN II. Nine feet across the tip-sails; weight 9lb 10oz; UNGER 18, energised by 20 Sanyo 1800 SCR cells and driving a 10 x 6 Tornado pusher; Futaba PCM radio. The little hatches are for dual parachutes, and the big one for a Minolta 35 AF still camera that, loaded and with servo trigger, scales 1lb 4oz. Total weight is just under the 11 pounds where our Civil Aviation Authority - the equivalent of your FAA - takes an interest.

I gave a paper on it to the Bristol International Remotely Piloted Vehicle Conference, which was well received. The Lockheed crowd promptly collared me, to trade information. They didn't quite tell me - they're not admitting this on the record - but made it clear that their Aquila, after a decade and a billion dollars, still exhibits exactly the snags I described, that are in the article you have. It avoids them by never entering those areas of flight, by never operating at high Cls. Ah, but what about landing? *What* about landing? No problem. It hits that net at 100mph. Plus!

There's one final MERLIN II on the stocks, with a Keller 25/16 and 16-cell battery; an inferior power system, but lighter - the idea is to save enough weight to let us lift a 16mm professional film camera, plus the solid-state TV and downlink (incredibly, six ounces together) that we've found essential to sight this, while remaining below that critical 11 pounds.

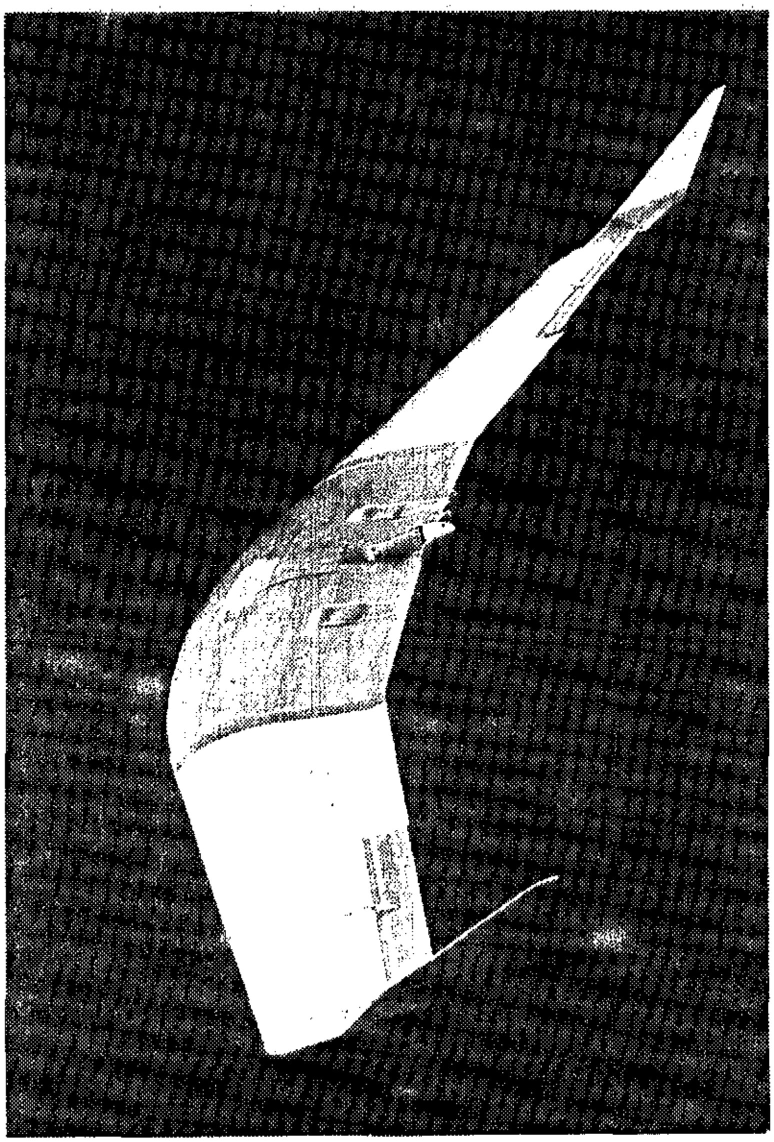
The MERLIN III will have new aerofoils. I've written to Michael Selig about this, but have had no answer yet - chase him, you need them too! We must know their behaviour with control surfaces deflected; there's nothing more critical to the acceptance of wings than understanding the non-linearities, and consequent cross-talk, in control response. If he doesn't come through I'll try the Eppler E-222, lofted to E-230 - on the advice of the Professor in person! We met at a super Royal Aeronautical Society meeting on low-RN aerodynamics, last October. I missed another good one this April, though, on tip sails, but I've asked Professor Spillman (our guru on this) for his paper. I'll pass Herk anything important.

You might mention to him that I'm looking at something slightly similar to his centre-elevator idea, but swept *forward*. We want to try propellors at the tips, which means motors out there, so for once a reverse-sweep bird might balance without a fuselage, and we'd be controlling yaw with differential power. The catch is that there's an awful lot of weight an awful long way out, which means high polar moments and sluggish response to "ailerons", with vulnerability to gusts as well as to crashes. On the other hand the cross-talk is minimised, and you can use a single central parachute. Incidently, it reverse-lofts, E-222 to the cambered E-230 at the tips. This is many months from cutting wood, let alone flying. Comments?

Yours sincerely

Noel Falconer

(Noel Falconer)



Ken Bates on Wings continued..... The "Keeper"

by Ken Bates

Having decided that "skid-roll" coupling caused most of the problems on P-4 and having confirmed this with "Sorta-Horten III", I took stock of what I thought I knew:

For the "pure" wing or highly swept wing of about 20° sweep and low to moderate (2°-4°) dihedral with small or no tip fins and small keel area.

The main limitation on performance is the skid roll coupling on tow. This causes a violent roll response to any yawing. The problem is related to tow strength (probably velocity most).

P-4 without fins and a small keel towed fine on a medium high start but with limited height. It also was slow going up the line - the 5/16" rubber just couldn't pull the 1700 sq. in. ship to its best height in low wind or calm. The tow problems all started when a high-power winch was used. Had these problems and others with tow set up not caused the early demise of P-4, a "safe tow might have been arrived at. However, since I really didn't understand what was happening yet, I proceeded with the "Sorta Horten". Since then I have seen several reports of P-4 type ships working on the high start, and one by Gene Dees in the U.S. using winch towing. Gene's ship has a "large keel in the center as well as tip fins. This confirmed what I found out on the "Sorta Horten" which did last long enough to learn a few things. I am still hesitant about the type for <u>high power FAI-style Launches</u> however. Gene is using flaps and has a modest wingloading. He is not perhaps using as severe a tow as the "Sorta Horten" required (not true! Herk Stokely used to flinch every time I used my "lead-footed" launch technique on high power with Icarosaur! ... Gene). The "Sorta Horten" finally worked with a keel so large it resembled the short fuselages seen in some of the British designs in the "White Sheet". My winch is a large 6-volt starter running on 12-volts with a large drum (5" normal 8" FAI). It draws 900 amps and is quite a "hard tow". Yet I feel that to equal our modern FAI and FAI derived conventional ships, our "wings" must abandon the undercambered reflex light wing loading mode and seek the high CL/ed airfoils used on current FAI machines, using them at the same type of loadings in order to realize their full performance (if your best airfoil L/D is at a lift coefficient of .7 at a Reynolds Number of 100,000 , you aren't going to get there with a 5 oz. wing loading !).

Also, my design goals for wings in general have had several assumptions and parameters attached. That is they must work in the standard U.S. contest rule framework; i.e., organizer supplied winches (no bungee . . . most being quite hefty these days, if you are called up to fly in a cross wind, you launch cross wind, downwind, or whatever or take a "0"), no special drop-off devices for extra stability during tow, and no auto-pilots or electronic stability devices including rate gyros or electrostatic pitch dampers. . . all stability must be rather inherent in the design or provided by pilot skill. This is the way I think it should be. Talk of electrostatic auto pilot systems for cross-country and the use of programmed push-button turn trim changes for FAI leave me cold! . . . that's another soapbox anyway!

With all this in mind cure the "Keeper" ,since the Sombra del Aquila had demonstrated excellent pitch pitch stability with 5° forward sweep and a conventional airfoil over most of the wing, I settled for 10° sweep back with a small amount of anhedral. This was to reduce the possibility of skid roll as much as possible while retaining an adequate amount of pitch stability. "S.d.A" had a large reflexed area in the root . . . "Keeper" was to have less. The airfoil chosen was an Eppler 205 in the root with a straight transition to a Bates 205 reflex at the tip . . . the twist was to be 4°. The anhedral should allow for a bottom single hook on a fuselage that had to be proportional rather deep to hold the radio as the model was to be a 2-meter type and the radio couldn't be conveniently buried in the wing (mine couldn't anyway!). Also the calculations of Michael Selig indicated that the 205 should have a rather low pitching moment.

These parameters also allowed for direct comparison with another conventional ship I own. This is a Pilot Harlequin modified to a flat wing with ailerons. As a 2-meter, multi-task type with a 205, similar area, frontal area, and wingloading I felt that this comparison might have more merit than the classic descriptive; "It's better than an Olympic II" which is usually applied to a wing doesn't resemble an Olympic II or have any similar design criteria or parameters.

FLIGHT TESTS

The first hand launch (toss) with the CG at a "normal" 19% caused me to jerk my foot back to avoid injury . . . nose heavy! Re-thinking, I realized the obvious (this happens a lot, as you know if you follow my "adventures in wing design"), being predominantly an un-reflexed wing, the CG was probably further back ! Well, the CG wound up at 25% right where it belongs on this type. Initially the CG was approximately 26% and I experienced an occasional separation-spin caused by an elevon deflection (you call them "ailevators" in Europe!). So a plastic gap seal was installed. This caused a noticable trim change from still somewhat nose-heavy at 26%

to somewhat tail-heavy (in effect). This brought the CG back to 25% for best trim (I think time will tell). The ship is not overly sensitive to CG location nor tow hook. The apparent max aft was found with controllable veering to one side or the other, not the sudden stall-pinwheel that I have experienced with some designs (Manx & pre-Windlord). The best trim is with the elevons up for a floating glide as the cores weren't fastened down during sheeting (foam) and the 1st skin took some of the twist out of the wing. The actual incidence or twist in the "floating" trim is 4° . . . originally intended however.

The ship has a slight "set" or histeresis at the minimum sink trim; i.e. a touch of "up" will produce a nose-high - slowly decelerating glide until stall, at which point a faster descending glide occurs. If left alone the ship will slowly accelerate to a high speed and return original trim suddenly (porpoising . . . Gene). A touch of "up" at the beginning will stop it. Whether this is due to a CG shift in the "unstable root area, or the slight sponginess in my conventional linkage (no "0" offset however) or "elevator snatch" (yes, that's what they called it!) . . . an up-force on the elevons that occurs near stall discovered by NACA and Northrop during their wing research of the early '40's, I don't know, in any case, the effect is small and not objectionable. The overall pitch damping appears to be between the Harlequin and a normal reflexed plank-type which always accelerates slowly when trimmed for minimum sink.

When a full power arc-over zoom launch is attempted, aileron flutter has occurred at maximum speed. This has not been experienced in flight or in the normal "ping" launch, although, vertical dives (unballasted) of only about 300 feet have been attempted. Acceleration is like the Harlequin . . . typical of the 205.

In the "distance" trim the ship is faster than the Harlequin and the slow speed pitch change is gone. The "Keeper" handles like any normal FAI type except being a little more sensitive on elevator . . . duel rates handle this nicely.

THE BOTTOM LINE

I ran a series of dead air trim tests. The wind was about 3 mph with a 90° crosswind to my launch. "Keeper" and "Harlequin" were launched on my Wookie winch with the same line length and time. The "Keeper" averaged 92% of the dead air time of the modified "Harlequin".

There remains the windy launch tests and the thermalling characteristics, etc. The long term true test is to campaign a wing in the conventional contest circuit for a season ("Keeper" did climb out for a couple of 10 minute flights).

WHAT'S NEXT

Maybe I'll just tweak the "Keeper". I can see several changes to make. The fuselage could be tapered and the rudder servo put in the center, getting rid of the "bat-tail". The current fuselage has room for a flap servo . . . that could be tried too. The interesting results of the hurriedly applied gap seal indicated that a better hinging system should be used. A rudder command near stall can induce a spin.

Not a "final" but a "Keeper" anyway.

Maybe a compromise between the "Elfe" type and "Keeper" is an optimum? I am leery of the skid-roll problem but, this could be the middle ground that would allow the high-power, high-speed launches I want or at least enough without resorting to so much slide area for the keel effect.

These quantities are still unknown: Does the Elfe rotate 80° or so on the tow and will it it do it on a powerful launching without problem? How much keel is required as size seems to matter?

More tests . . . more reports of other's efforts and maybe we will all get closer.

"Let's catch the 5 o'clock pteradactyl to Frantic City !"

---- Fred Flintstone to Barney Rubble

Don Klahre's Pteradactyl

Excerpted from a letter to Gene Dees from Don Klahre, aged 15, of Little Silver, NJ
June 1986

From reading about Dr. MacCready's pteradactyl, I saw it has a computer brain. Knowing that putting one in my bird is impossible, I devised a magnetic steering system that makes the head compensate with the wind when I am not using the steering servo. I am using 3 Futaba servos. Beginning construction of the bird was hard because I had to stack the 1/8th inch wide balsa body ribs on leggo bricks. Then I took 1/8" x 1/16" balsa strips and connected the ribs with them. The trailing edge is 1/4" wide and 1 inch long. The wing squares are 2-3/8"x 2-5/16. The altitude of the body is 6 inches and the length from head to foot is 3 feet, 1/4 inch. The tail fin is not permanent and is easily removed; it serves as the bird's stability as I get used to flying it. All material on the bird is balsa with the exception of the nails on the neck and the wing bindings. The FP-S28 Futaba servos are placed too far in the back of the bird so I feel I have to put my steering system in the front of the bird. The wing span is 6 feet.

When the pteradactyl finally gets through the red tape of the editors, please tell me what edition it will be in. By sending me your letter, you made my year, after all, it did take 1/15th of my life to make the pteradactyl.

AIAA'85

AIAA-85-1446

Development of a Wing-Flapping Flying Replica of the Largest Pterosaur

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AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference

July 8-10, 1985 / Monterey California

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DEVELOPMENT OF A WING-FLAPPING FLYING REPLICA OF THE LARGEST PTEROSAUR

Alec N. Brooks *
Paul B. MacCready **
Peter B.S. Lissaman ***
Walter R. Morgan ****

AeroVironment Inc.
Monrovia, California

Abstract

Fossil evidence exists for a gigantic pterosaur, *Quetzalcoatlus northropi*. This flying reptile, with a wingspan estimated at 11 m, represents the largest flying animal known. A project is underway to create a full-sized flying replica, designated the QN^{tm}* replica, to be propelled by wing flapping and controlled by radio. The need for the reconstruction to fly in a manner analogous to the original creature is requiring engineers and paleontologists to combine forces to bridge gaps in knowledge about natural flight.

The replica will use electric servo-motors to flap, sweep, and twist its wings. The head and fingers (located about halfway out on the wing leading edge) will also be servo driven, for use as lateral control devices. An autopilot will maintain angle-of-attack, bank angle, and sideslip angle. Pitch control will be effected using variable wing sweep, with the wings pivoting about a pair of approximately vertical axes located in the body.

Introduction

Pterosaurs were a class of flying animals distinguished by their reptilian features and slender membranous wings, and lived during the Mesozoic era, between about 200 million and 64 million years ago. The wings of pterosaurs are formed by the greatly elongated fourth finger of the hand. The larger pterosaurs had no tails, and were thus 'flying wings'. All pterosaurs were very lightweight, and had very thin-walled hollow bones. An excellent introduction to pterosaurs is given by Langston in a *Scientific American* article[1]. The name 'pterosaur' derives from the Greek words *pteron* and *sauros*, literally 'winged lizard'.

In 1975, fossil remains of a giant pterosaur were found in West Texas by Lawson[2], working with Langston. The new species was named *Quetzalcoatlus northropi*, after the Aztec feathered serpent god, *Quetzalcoatl*, and the Northrop Aircraft Company, which built several giant flying wings in the 1940's. Except for one vertibra, only some of the wing bones were found, and many of them were crushed and distorted. As a result, a detailed reconstruction has not been possible. The existing wing bones suggest a wingspan of about 11 m. The mass is much more difficult to determine. Based on considerations of power required to fly, the mass must have been 100 kg or less.

Another group of fossils was found at the same time for a smaller, but similar creature. This group contained nearly complete skeletal remains of several specimens. Due to the similarity with the larger fossils, this group was given the name *Quetzalcoatlus sp.* (sp. is an abbreviation for 'species'; when more is known about these fossils, a genus name may be assigned). Langston is currently reconstructing a complete skeleton of *Quetzalcoatlus sp.*, to provide insight into what the larger creature might have been like.

The QN^{tm} Replica project

In April 1984, a National Air and Space Museum (NASM) project was initiated to investigate the feasibility of constructing a flying replica of *Quetzalcoatlus northropi* (figure 1). At the beginning of the project, AeroVironment convened a QN^{tm} Replica Workshop at the California Institute of Technology to help assess the overall feasibility of building and flying the replica, to make plans for later phases of the program, and to arrive at a consensus about the size, shape, and operating features of the creature. The workshop brought together experts in paleontology/paleobiology, ornithology, aerodynamics, stability and control, robotics, and also representatives of the NASM.

The workshop concluded that construction of the replica was certainly possible, with the two main problems being stability and control, and

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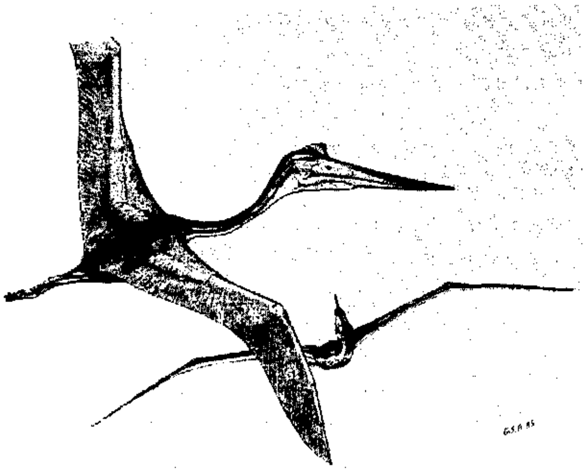

Figure 1. Artist's rendering of Quetzalcoatlus northropi (Gregory Paul, Artist).

wing-flapping propulsion. In December, 1984, a press conference was called at the NASM to announce the positive results of the initial feasibility study. With AeroVironment as prime contractor, the project then continued into the development stage with major funding from Johnson Wax supplementing the NASM support.

Overall approach to QN^{tm} Replica Development

The plan for creating the final replica was to solve the major technical problems one at a time, using a series of increasingly complex flight models. Stability and control were perceived to be the really difficult problems, and so were addressed first.

The stability/control challenge arises for several reasons. First, Quetzalcoatlus northropi had no horizontal tail to deal with with stability and control in pitch. Also, its wing may have been unstable in pitch, due to its undercamber and lack of sweep. Second, there is no vertical fin or rudder to provide lateral control, and there is a long neck and large head, which produce destabilizing directional derivatives.

To fly stably, the creature must have made use of active control. For example, variable wing sweep was probably used to continually adjust the fore/aft position of the center of lift relative to the center of gravity. Humans utilize active control in many situations, such as riding a bicycle or standing on one foot, without being aware of it — it is simply instinctive. For the replica, this control involves motions which might seem natural: wing tips forward produce a pitch-up while if the head turns to look to the right, a right turn is initiated.

The flight models being tested prior to building the final 11-m replica include a pitch control development model with a standard aircraft configuration, a half-scale lateral control development model with pterosaur configuration, and a half-scale, realistic flapping model.

All stability and control analyses and autopilot control loop design for the QN^{tm} replica project are being performed by Henry R. Jex, of Systems Technology, Inc.

Pitch Control Development Model

Pitch stability and control on the replica will be effected using variable wing sweep, actively commanded by an autopilot. A 2.5-m span radio-controlled glider was built to develop this capability. It had a standard configuration but incorporated servo-driven variable-sweep wings, pivoting about a vertical axes in the body. During initial flights, variable wing sweep provided the sole pitch control, with a fixed horizontal stabilizer on the tail to provide stability. An autopilot was then added which commanded the wing sweep angle, using sensed angle-of-attack and pitch rate. Test flights continued using smaller and smaller horizontal tails, as the autopilot feedback gains were optimized. The final flights of this model were made with a very small horizontal tail, barely extending past the tail boom to which it was mounted.

The servo used to drive the wing sweep was a large, commercially available model airplane unit, which was barely adequate for the job. Its response bandwidth was marginal for the task of maintaining pitch stability, resulting in considerable 'hunting' of the wing sweep position in flight. The final replica will use a custom made servo with faster response.

Lateral Control Development Model

A half-scale (5.5 m span) gliding model is being used to develop the lateral control functions. This model, shown in figure 2 along with many members of the development team, has the general configuration of the final replica, but for simplicity does not incorporate variable wing sweep. For this vehicle pitch control is achieved using trailing edge elevators on the inboard section of the wing. The wing structure is rigid, made of expanded polystyrene foam with a carbon and balsa spar, and uses a reflexed Liebeck airfoil.

Lateral control surfaces include the head, which pivots about the neck to 'look' from side to side and generate yawing moments, spoilers about halfway out on the wing which can create drag and reduce lift, and ailerons on the trailing edge of the wing. On the next model, the spoilers will be replaced by more realistic moveable fingers, and the ailerons by variable wing twist. An autopilot controls these surfaces using signals from a sideslip vane and a yaw rate gyro, as well as commands from the ground.

With a weight of more than 11 kg, this model is too large to be hand-launched from a hill, so a winch tow is used. To enhance stability while on tow, an auxiliary set of tail surfaces is fitted, which is dropped off after completion of the tow. The auxiliary tail also has wheels for takeoff and a parachute for recovery after it is dropped. The model is fitted with an emergency parachute which can be deployed in the event of loss of control.

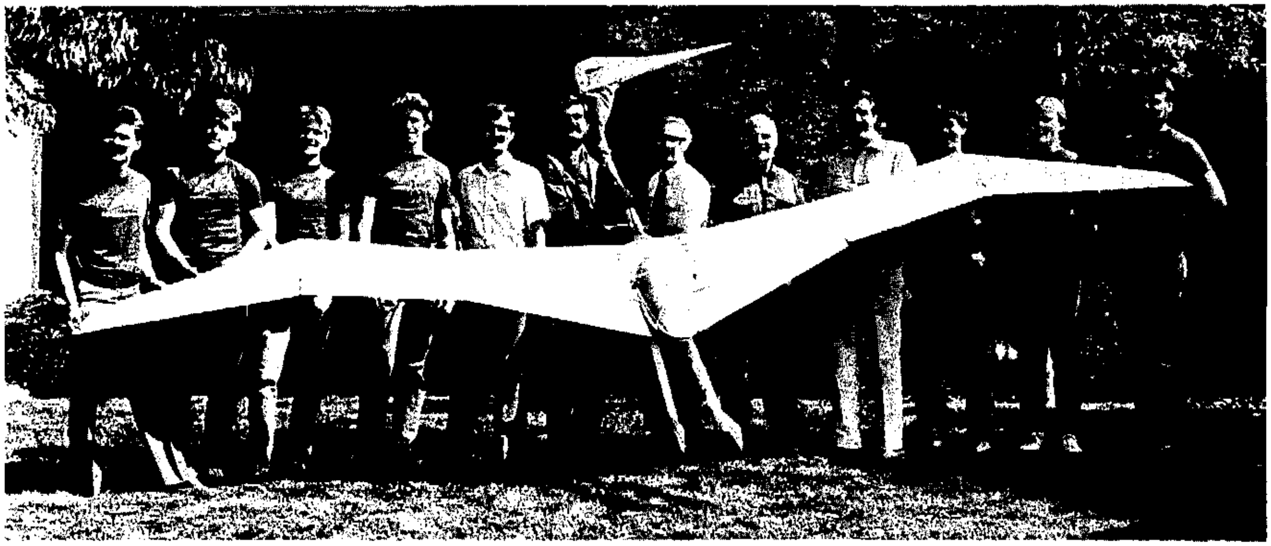

Figure 2. The lateral control development model and the project team.

Figure 3 shows the model in flight shortly after release of the tail.

The head is commanded to provide a stabilizing and correcting yaw moment by turning toward the relative wind at an angle greater than the sideslip angle. Yaw damping is added to the head command using the sensed yaw rate. The spoilers are principally used as yaw dampers. The ailerons have been initially directly commanded by the pilot, but later will be controlled by a wing-leveling autopilot.

Flights with this model have shown stabilization in yaw to be a very difficult problem, analogous to trying to fly a normal airplane with the vertical tail moved from behind to in front of the wing (i.e. with negative directional stability). Successful flights have been made under nominal flight conditions, but the system is not yet 'robust' in that under some other conditions apparently related to large excursions from equilibrium, such as excessive airspeed or momentary radio 'glitches', complete loss of control is possible. This occurs when the sideslip angle increases to an angle at which the head and hands can no longer provide adequate restoring forces. In this instance the head acts as a 'weathervane' and the model quickly turns sideways and falls uncontrollably, necessitating a parachute recovery. Further development of the system will reduce the probability of loss of control.

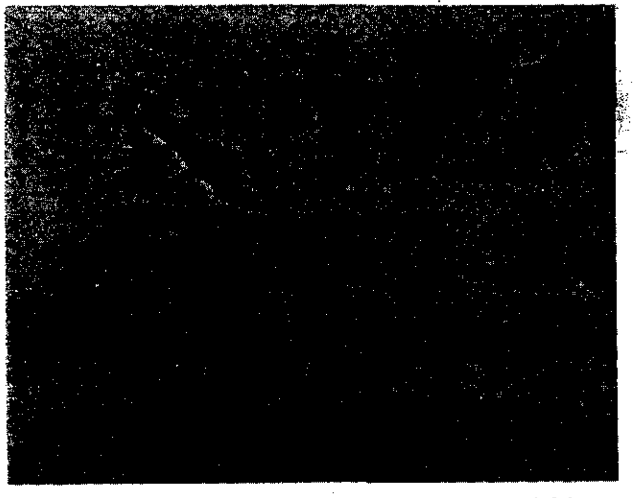

Figure 3. The lateral control development model in flight just after release of the auxiliary tail boom.

Half-Scale Flapping Model

After development of the lateral autopilot system is complete, a realistic flapping-wing half-scale model (5.5 m wingspan) of Quetzalcoatlus northropi will be built and flown. This model will be the prototype for the final full-scale replica, incorporating all of the final control functions. It will be the same weight and size as the lateral control development model, and will also be winch-launched with an auxiliary tail boom. Before flight testing with flapping, it will first be flown as a glider until all stability and control problems are resolved. Flapping tests will proceed gradually, starting with captive tests with the vehicle mounted on top of a moving van, then proceeding to flight tests with small flapping amplitudes with the auxiliary tail still attached.

Details of the flapping aerodynamics and the flapping mechanism design are given below.

Ornithopters

Although birds make flapping flight look easy, it has proven to be a challenge for man to mechanically reproduce. Man-made flapping-wing flying machines are known as ornithopters. Attempts to build ornithopters can be split into two categories: man carrying, and hobbyist/toy. Only the hobbyist/toy ornithopters have shown any successes at all.

There are many good small rubber-band powered ornithopters, with wingspans of 0.5 m or less. Rubber bands are a good power source because they can deliver the necessary torque directly, without resorting to a gearing system. However, rubber bands do not have high energy storage density, so flight duration is quite limited.

Larger ornithopters have been built using compressed gas or model airplane engines for propulsion. At the QN^{tm} Replica Workshop, two of the participants presented results of experiments with large 3-m span radio-controlled ornithopters.

Bennett conducted his doctoral research on ornithopter aerodynamics[3] and later tested a large ornithoper mounted on a moving test rig that was instrumented to measure lift and thrust. The wings were initially built to allow twisting as well as flapping, but proved to be too flexible in torsion. A torsionally stiff set of wings that eliminated twist were used for the tests. This wing was stalled during much of the flapping cycle, and it was found that net thrust and lift could not be generated simultaneously.

Flight test films of a large twin-engine radio-controlled ornithoper were shown by Adkins[4]. One engine drove a variable amplitude flapping mechanism, and the other was mounted in the nose driving a normal model airplane propeller. Both engines would be started on the ground, with the flapping amplitude controller set to zero. The model could then take-off as a normal airplane and climb to a safe altitude. The front engine was then throttled back, and the flapping amplitude was slowly increased. In the event of incipient instabilities, the flapping could be immediately shut down, and a normal landing could be made. While flapping, this model was capable of climbing at very steep angles.

Aerodynamics of Flapping Flight

Flapping-wing propulsion is relatively simple in concept, but accurate calculations are difficult due to the complexities of the intrinsically unsteady flowfields involving both viscous and potential unsteady effects. In simplest terms, if a wing in a uniform flowfield is oscillated in heave only (no pitch change), then a net thrust can be developed. The basic case is that of a wing initially at zero angle of attack. When this wing undergoes heave motions, the local velocity vector is inclined, causing the lift vector (approximately perpendicular to the local velocity) to be inclined forward, resulting in a thrust component. This thrust is developed on both up and downstrokes, while over a complete cycle the lift component cancels out. If the wing also undergoes pitch angle oscillations properly phased with the heave oscillations, the thrust generation can be more efficient, with smaller variation of the lift coefficient during the flapping cycle. By biasing the pitch angle of the airfoil, a net average non-zero lift can be created along with thrust. This is the basis of flapping flight. Based on the foregoing, it can be seen that a condition for net thrust as well as net lift is that the lift on the downstroke is greater than the lift on the upstroke. It is noted that this condition provides the mechanism for work to be done by the flapping drive mechanism which is then transformed, with an inevitable efficiency loss, into propulsive power.

The fluid mechanics of flapping flight involves intrinsic unsteady effects. To establish a basis for the discussion following we will list them here. The analysis of unsteady potential flow is very well understood. The principal elements here which are not present in steady flows are the spanwise shed vorticity downstream of the wing and the pressure perturbations on the wing due to the temporal derivatives of the potential (sometimes referred to as apparent mass terms). While the exact equations for the fluid dynamics can be simply formulated, the complexity of the integrals required for solution severely limits any closed form analytical solutions and requires numerical computation for most realistic geometries. The unsteady effects in the viscous (boundary layer or separated flow) regions are still incompletely understood. In addition, the nonlinear effects of large perturbations add further complexity and in general inhibit separation of variables or superposition of various fundamental situations such as the flap-with-no-lift and the lift-with-no-flap cases.

Observations of wing motion in some bird flight modes indicate that the wing-stroke is very complex involving fore and aft as well as up and down wing motion, extreme articulation (changes in wing angle of incidence) and large flapping motions, all with pronounced spanwise variation. However these modes often involve very low speed or highly accelerated flight. For regular cruising flight with steady average forces it is probable that the wing motion is much simpler. This is representative of the mode with which we are concerned.

The wing flapping dynamics will be designed to incorporate essentially a uniform vertical flapping motion pivoting about the root, with articulation achieved by the aero-elastic effects of a spanwise-taylored torsional spar stiffness, assisted by servos which directly twist the wings. Thus, for this project it is desirable to obtain some crude guidelines on appropriate flapping lift distributions and on the consequent propulsive efficiency, and to use these as a starting point, with the prospect of fine-tuning the propulsion dynamics by actual testing. No unsteady viscous analysis has been employed on the basis that these effects occur only near the stall angle of attack. It has been assumed that, provided the steady state stall angle is not exceeded, the unsteady viscous effects will not be significant.

Two potential flow models (Kroo[5] and Bennett[3]) have been used as guidelines for the flapping design. A simplified quasi-steady lifting line model has been given by Kroo[5] which does not include the effects of both spanwise shed vorticity and apparent mass, but does incorporate articulation and a realistic flapping motion. This model gives an optimal flapping lift distribution which corresponds to the steady-state lift distribution which would result in a spanwise downwash varying like $|y|$, where y is the spanwise parameter (y=0 at the root, y=1 at the tip). This is a special case of the general steady wing theory result that, on a wing of spanwise circulation $\Gamma(y)$, the induced drag is minimized, subject to an integral weighting parameter f(y), under the condition that

$$\int_0^1 \Gamma(y)\, f(y)\, dy = P$$

is constant. This is satisfied by selecting $\Gamma(y)$ such that the steady state induced downwash is proportional to the weighting function, f(y).

If f(y) is take as proportional to the vertical motion at the spanwise station y, it will be noted that P represents the input flapping power. Putting f(y) = 1, representing heaving motion, recovers the classical elliptical loading as optimal, while the case $f(y) = |y|$ represents the motion of flapping about a horizontal hinge at the wing root. The flapping circulation associated with this downwash is a characterisic saddle-back distribution. The design flapping lift distribution is shown in Figure 4 where it is superimposed on the steady state elliptical mean lift distribution to indicate the maximum and minimum lift during a cycle.

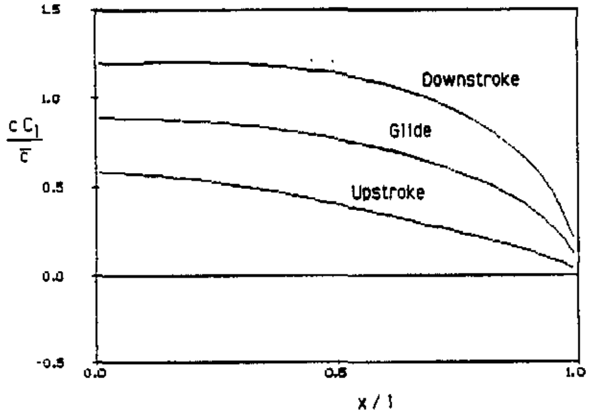

Figure 4. Optimum flapping lift distributions at mid-points of upstroke, downstroke, and glide.

The thrust coefficient, T_c, is nondimensionalized similarly to the lift coefficient, thus it is defined as the thrust divided by the wing area and dynamic pressure due to forward flight speed. Figure 5 shows how the thrust coefficient and the flapping frequency influence the required variation of total lift coefficient. Also shown are the predicted propulsive efficiencies and the design point for the half-scale replica. The prediction of an efficiency in excess of 98 percent is evidently a consequence of the factors ignored in the quasi-steady model. The parameters at the design point are: flapping frequency, 1.2 Hz; average lift coefficient, 0.7; flapping lift coefficient, ±0.32.

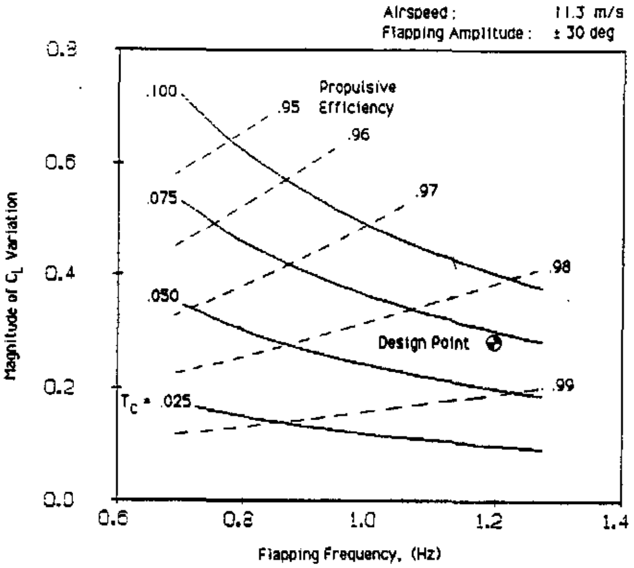

Figure 5. Magnitude of the fluctuating lift required to produce given thrust coefficients as a function of flapping frequency.

The model of Bennett takes into account the spanwise shed vorticity, the apparent mass terms and the lifting surface effects (as opposed to lifting line). However it is for a non-articulated rectangular wing undergoing heaving motions. However, it can be assumed theoretically correct for this simplified geometry. This model gives a limit case for vanishing frequency (the quasi-steady case) and thus provides an estimate of the error involved in the quasi-steady case.

For a reduced frequency (based on semi-chord) of 0.13 and a thrust coefficient of 0.1, Bennett gives the ratio of the actual thrust to the quasi-steady value to be 0.75 for an elliptical planform of aspect ratio 14 and 0.5 for a rectangular planform of the same aspect ratio, while the propulsive efficiency is 0.92 and 0.75 for each planform, respectively.

The difference between the Kroo and Bennett results, although in part due to different parameters, illustrate some of the uncertainties which have made it prudent to make design allowances for a low propulsive efficiency and to be able to modulate the wing articulation.

At present, the design strategy is to use a selected flapping lift distribution and to determine by approximate methods the local induced and flapping-created vertical flows so that the proper twist or articulation of the wing can be achieved. For the replica, this articulation is of the order of 45° at the wing tip, considerably greater than the twist of the order of a few degrees associated with the spanwise variation of the desired flapping loading. It is unlikely that the twist can be either predetermined or controlled to so fine a degree, and as a result the flapping propulsive efficiency will suffer and it will be necessary to increase the power input to achieve the desired performance level.

Mechanism and structure

The predicted efficiency of flapping flight is quite high (at least in excess of 80 percent), and yet man-made ornithopters always seem to be very inefficient. This may be due mainly to the large oscillatory motions required to flap the wings. Fairly large forces are required at the end of each flapping stroke to slow the wing and reverse its direction. This in itself does not require energy because during deceleration the force is in opposition the direction of motion so work is done on the mechanism. If this work is stored, it can be recovered as the wing accelerates in the opposite direction. It is believed that birds use springy tendons to store this energy. Many ornithoper attempts have not adequately addressed this issue, and therefore operate nonconservatively, and thus dissipate part of the kinetic energy of the flapping motion. The QN^{tm} replica will utilize a spring to balance the inertial flapping loads, with the resonant frequency of the system matched to the flapping frequency. In addition, the spring will be pre-loaded to balance the steady state gliding lift loads.

Flapping mechanism design philosophy

The flapping mechanism for the QN^{tm} replica requires three independent motion controls: flapping, sweeping, and twisting. The flapping and sweeping motions operate on both wings symmetrically, while the twisting motion must be capable of operating differentially for roll control.

Several options were considered for the wing-flapping mechanism of the replica. One of the ground rules from the start was that it should be electric powered to keep the noise level low. An electrically-driven hydraulic system has many advantages, but was ruled out due to unacceptably low efficiency.

Another option, similar to systems used in most previous ornithopters, is a geared DC motor which drives a reciprocating mechanism. In this case the motor runs steadily at high speed, but with variable torque throughout the flapping cycle. The phased twisting of the wings would be accomplished with a mechanism. This requires a motor controller that varies the applied voltage to the motor over the flapping cycle in order to maintain constant speed. If remote control of flapping amplitude is desired, the there must be some means of varying the geometry of the drive mechanism. The mechanism of the Adkins ornithopter had these features (but not variable sweep), and was quite complicated.

The mechanism design chosen for the replica uses servo motors to produce all of the wing motions, including flapping. The flapping servos use DC motors, as in the previous option, but instead of using a reciprocating mechanism for motion reversal, the motors in the servo reverse direction. The advantage of this system is that the wing flapping motions are easily modified, since this information is stored in software, rather than hardware.

The mechanism for the half scale replica uses ball-nut drives to convert high-speed rotary motion of the motors into low-speed linear motion. The wing roots are pivoted on a gimballed joint at the 'shoulder', and a stub spar extends inward to nearly the centerline of the body. Links from the flap and sweep ball-nuts attach to the end of the stub spar. The partially completed mechanism of the half-scale replica is shown in figure 6. The flapping motion is driven by two Astro-Flight model 60 Samarium Cobalt DC motors geared 1-1 with the ball screw. These motors are each rated at 900 W peak output power. A single sweep motor, an Astro-Flight 05, directly drives the sweep ball screw.

Spring Balance

The flapping mechanism incorporates a spring which balances inertial and steady state lift loads in the mechanism. The spring rate is chosen such that the natural frequency of oscillation of the mechanism is equal the flapping frequency, and the preload is set to balance the average lift loads. In addition to the wing inertia, the inertia of the motor armatures, gears, and other rotating components must be considered when calculating the appropriate spring constant. The motor inertial loads account for 85 percent of the total. Each motor is required to

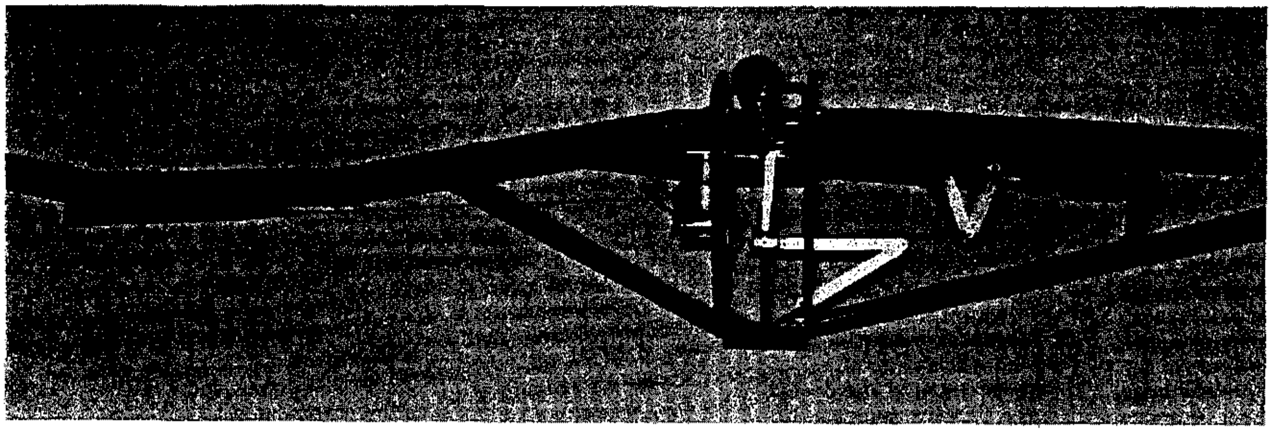

Figure 6. Internal body structure and flapping mechanism of the half-scale flapping replica (under construction).

accelerate from zero to 9000 rpm and back to zero again twice during the 0.83-second flapping cycle.

The spring balance for the replica is made of rubber of the type used on rubber-powered model aircraft. The spring is about 0.15 m long, with multiple strands of rubber. It is fixed at one end to an attachment point on the neck, about halfway between the body and the head. The other end is connected to a length of braided fishing line. This line winds up on a spool attached to the intermediate shaft of the main gearbox. The line is able to wind on either side of the spool, to allow the spring to the spool. In order to balance the steady state lift loads, this point is set to occur at an appropiate anhedral (wing tips below horizontal) position of the wings. The peak compressive loads in the neck due to the spring are about 350 N. Operation of the spring balance is depicted in Figure 7.

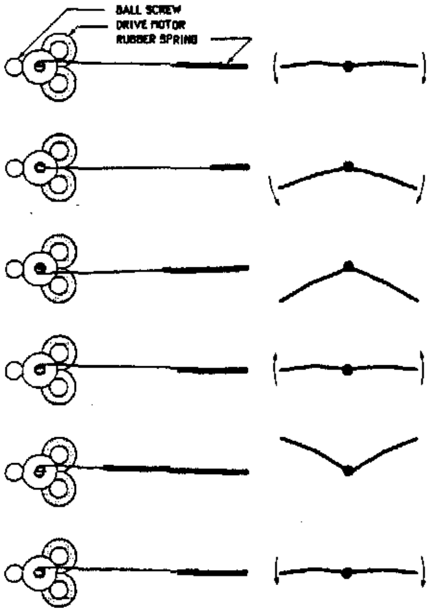

Figure 7. Operation of the spring which balances the inertial loads associated with flapping.

The spring balance relieves the flapping motors of heavy braking and acceleration loads. If the spring balance were not used the motors and servo amplifiers would have to be significantly larger, and energy would be wasted due to the higher currents required. Figure 8 compares the current and voltage requirements for each motor over one flapping cycle with and without spring balancing of the inertial loads.

Wing Twist

The wings must twist through large angles during the flapping cycle to maintain the proper loading. The replica's wings will be made flexible in torsion, allowing most of the required twist to be achieved passively by aeroelastic effects. Small servo motors will be used to fine-tune the elastic twist. The spanwise distribution of torsional stiffness of the spar is calculated to give the proper torsional deflection given the variation of lift loads and required twist angle over the flapping cycle. In addition, the wing is built with a calculated 'pre-twist', such that in gliding flight, the wing will be deflected to the proper shape.

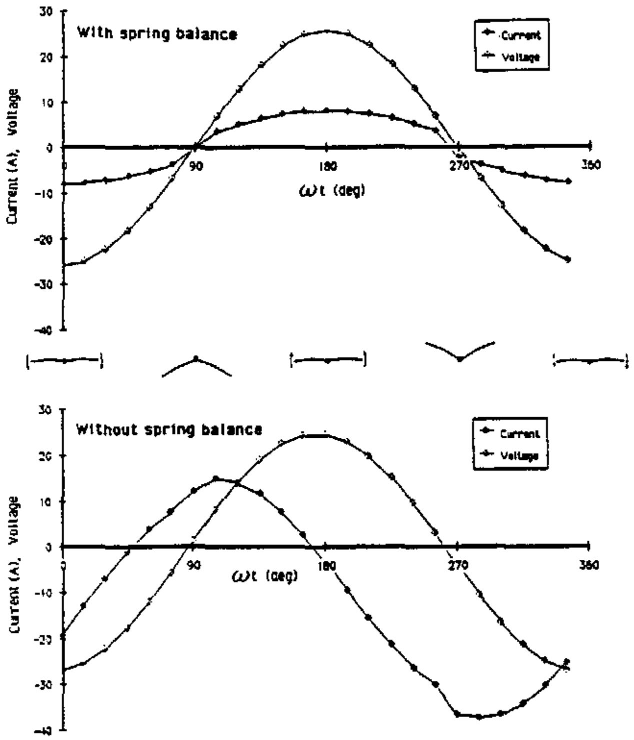

Figure 8. Comparison of current and voltage requirements for each flapping motor with and without the spring-balance.

The wing twist servos each actuate a torque tube that runs inside of the main spar to the point about halfway out the span where the large fourth finger meets the hand. The twist servos will be commanded to follow a certain twist angle over the flapping cycle. If the passive twist accurately follows the desired twist, then the twist servos follow the motion with virtually no load. Otherwise, the twist servos apply torque to force the wing to the correct twist angle. The servos twist the wings differentially for roll control.

Power System

The electric power system for the replica demands very high power density from the energy source, with reasonable energy density. To meet these criteria, the replica will use high-discharge-rate sintered-annode nickel-cadmium cells. These are commonly used in electric-powered model aircraft, and can produce about 250 W/kg over a discharge of 4-5 minutes. The half-scale replica will carry two strings of 28 "sub-C" size cells, which have a total weight of 3 kg.

Delivery of the power to the various servos will be through commercially available FET-based servo amplifiers. These amplifiers are pulse-width-modulated at 22 kHz, with full four quadrant operation in the voltage/current plane. This allows bi-directional motor drive with dynamic braking.

The radio receiver and autopilot circuits will be powered with a separate 5 V battery pack.

Control and Autopilot System

The control system for the replica will incorporate lateral and pitch autopilot functions. The pilot on the ground will command the angle-of-attack, turn rate, and flapping amplitude. The control system is based on standard model alplane radio control (RC) hardware, customized where required. Standard RC systems command each servo with pulse-width modulated (PWM) signals. The autopilot functions for the replica are accomplished by converting the PWM signals to analog levels, then adding in appropriate amounts of sensed quantities (e.g. yaw and pitch rates, angle of attack, sideslip angle). The resulting signal is then either converted back to a PWM signal for driving standard model servos, or sent directly to the FET servo amplifiers for driving the custom servos.

The wing-flapping servo amplifier must receive a flapping waveform signal. The simplest case is a sine-wave at the flapping frequency with its amplitude set by the pilot's command. The wing twist signal is generated by scaling and phase-shifting the flapping signal. The flapping motion may also require cyclic motion of the wing sweep servo to minimize pitching while flapping. For the greatest flexibility, these signals will be generated by a digital circuit which scans through lookup tables stored in read-only memory.

Conclusions

The task of creating the QN^{tm} replica requires creative application of a diverse range of existing technologies to find engineering solutions to problems that nature solved millions of years ago. As development of the replica has progressed, we have developed a great deal of respect for nature's solutions.

The replica will have only a handful of motion degrees of freedom, controlled by relatively 'dumb' autopilot circuits. The actual creature had a great number of individual muscles, controlled by a brain with relatively immense processing power. In addition to flying, the creature was also cabable of standing, walking, and running for takeoff. The replica will not attempt any of these feats -- Man-made robots have not yet even come close to recreating the versatility and dexterity of the human body.

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Acknowledgements

In addition to the 15 members of the project team at AeroVironment, many enthusiastic experts are actively involved and have donated their valued skills. We would especially like to thank George Bennett, Robert Boucher, Alan Cocconi, Henry Jex, Ilan Kroo, Wann Langston, Robert Liebeck, Kevin Padian, Gregory Paul, and Michael Vail. We also wish to gratfully acknowledge the financial support of the Smithsonian National Air and Space Museum and S.C.Johnson & Son, Inc. for the the QN replica project.

"I feel like a King in my Flying Wing."

---- sung by ' The Lightning Bug'

---- from the underground cult classic movie **J-Men Forever**

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AIAA Professional Study Series

THE GOSSAMER CONDOR AND ALBATROSS: A CASE STUDY IN AIRCRAFT DESIGN

16 June 1980

By James D. Burke

Report No. AV-R-80/540

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FOREWORD

This AIAA Case Study is an account of two new airplane developments. It focuses on the design and testing of the aircraft themselves, and must therefore omit many important subjects in the program as a whole. In the text I have used people's names when it seemed natural to do so, but it must be remembered that vital contributions were made by many others in addition to those named -- not only as volunteers at various times on the development team, but also in other roles. For example, the people who made it possible for us to use hangars at Mojave, Shafter, Terminal Island, Nellis, Manston, and the Warren were essential contributors. The observers designated by the Federation Aeronautique Internationale (FAI), though prohibited from sharing in the fun of building and flying the aircraft, patiently attended our trials, investing long hours of their own time so as to be able to certify that the set tasks had, in fact, been achieved. The people who documented our efforts on film, the people who recruited the major sponsor, the Du Pont Company, and the other corporate and private sponsors, and of course the sponsors themselves, made indispensable contributions -- not only in funding but also in many other kinds of advice and support. People in Britain extended endless hospitality and assistance, as did those involved at the other end of the cross-channel flight in France.

Finally, of course, the whole effort was made possible by the generosity and sporting spirit of Mr. Henry Kremer, who, with the Man Powered Flight Group of the Royal Aeronautical Society, has brought something totally new into the world, fulfilling an ancient dream.

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1. INTRODUCTION

The Gossamer Condor opened up new prospects in the field of human-powered flight. Designed and built by Paul MacCready and a team consisting of his family and friends, it is the first and so far the only muscle-driven airplane to complete the figure-eight flight required for the Kremer Prize. On 23 August 1977, at Shafter, California, Bryan Allen flew the Condor around the Kremer course in about 7-1/2 minutes. On 12 June 1979, Allen, flying a more refined airplane called the Gossamer Albatross, succeeded in crossing the English Channel despite troublesome air turbulence and a headwind that arose on the way across. He was aloft for two hours and 49 minutes, far exceeding the duration of any other human-powered flight, and his supreme effort won for the team another Kremer Prize.

The Gossamer Condor, shown in flight in Figure 1, is now displayed in the U.S. National Air and Space Museum and the Gossamer Albatross, shown crossing the Channel in Figure 2, is visiting other museums in the U.S. and Europe. Meanwhile, development continues in California using two backup aircraft as test vehicles (Figures 3 and 4).

These airplane projects are remarkable in many ways and the purpose of this Case Study is to record some of their unique technical aspects. However, those are only a part of the story. The venture is unusual not only in its engineering creations but in its motives, methods, and rewards. Since these too may have relevance in other fields, I shall describe them briefly as I discuss the progress of designs and tests. In this Case Study I plan first to discuss the program's objectives, methods, and chronology, next to review performance, aerodynamics, stability, and control, then to discuss structures and instrumentation, and finally to describe how all these evolutionary developments came together in the cross-channel flight of the Gossamer Albatross.

2. PROJECT OBJECTIVES AND PRINCIPLES

The prizes offered by Henry Kremer and administered by the Royal Aeronautical Society are in the spirit of aviation's early days: Flight performance is everything, and the other commercial or military criteria that usually surround a new airplane project are absent. Also, because the Kremer contest airplanes can fly slowly and at altitudes of only a few feet, safety is not a dominant factor in their design.

The Gossamer Condor was conceived as a machine with but one purpose: to be propelled just once around the Kremer course (Figure 5), by a human under FAI observation, and so to win the prize. The central idea, discussed quantitatively in Section 4, was to fly more slowly than previous contestants, so that a weight-saving, wire-braced structure could be used. Though the pilot would have to pedal longer, it looked as if the power required could be reduced more than enough to compensate. However, it was obvious that such an aircraft would be totally impractical for any but its intended purpose. An immense hangar would be needed and a moderate gust of wind would probably destroy the machine. These constraints were accepted in the belief that somewhere in Southern California a suitable flying site could be found. Throughout the development of the early Condors (Figures 6 and 7), similar choices were made. The project abounded in opportunities for interesting research, but MacCready resolutely put them aside in order to keep attention focused on the central goal. As a result some of the fundamental technical data that one expects to see on a new airplane simply do not exist. However, this approach did surely provide short paths to design solutions. We attacked only the most obvious problems, intending to deal with others if and when they arose. We concentrated on gaining flight experience without stopping to correct minor deficiencies: note the milk-bottle ballast in Figure 7. Through hundreds of flights and many crashes the design refined itself into that of the final Condor without ever departing from the original basic configuration, a canard pusher with the pilot suspended on wires under the wing. This structural concept permitted the quick repairs and modifications which, together with the slow flight speed, were the keys to the Condor's success.

Though the project's object was single, its rewards were multiple. During the arduous and often disappointing work of developing the Condor, all involved shared in the magic of using our own ideas and our own hands to create things that had never existed before. In the interest of brevity and conciseness, later sections of this Case Study may make it seem that we were always deadly serious and always knew what to do next. We were indeed serious in our intent to quickly win the prize. MacCready exhibited a remarkable concentration on that one goal and a steady confidence, based on his analyses of the central performance parameters, that we would eventually achieve it. However, in trying out new ideas we encountered again a well-known aspect of innovation: often it is most successful when it is not pursued too doggedly. As Peter Lissaman once put it, "Levity should be a prime concern for aeronautical engineers." Our flight-test outings were family affairs with a fluctuating crew of builders that usually included MacCready, Lissaman, Jack Lambie, Bill Beuby, Kirke Leonard, various Burkes, and a few others plus a good complement of kids, skateboards, dogs, bikes, and aircraft of all sorts. Bizarre inventions flourished; one could write a whole Case Study just about the models that filled the air. Our design conferences took place at hangar picnics and during the flights or long night drives to and from the test sites. If somebody wanted to try something he collected scrap from the last crash, went to a corner of the hangar, and built it. Seldom did a proposal receive the response, "that won't work because . . ." and always there were the slow, dreamlike flights of the great, silent aircraft in the calm of deserted airfields at dawn.

3. CHRONOLOGY

To help set the scene for our Case Study, in this section I shall outline the sequence of project events. The prior background of human-powered flight is well reviewed in References 1, 2, and 3. References 4, 5, and 6 are representative papers on the Gossamer Condor and Albatross that have already appeared in the technical literature. Reference 7 gives Bryan Allen's own story of the Channel crossing, while References 8, 9 and 10 are the best examples of coverage of that event in the aeronautical press. Reference 11, to be published within the next year, is intended to be a complete history of the Condor and Albatross developments.

MacCready's idea for a new way to win the Kremer prize came during a hang-gliding, bird-watching vacation trip during the summer of 1976. The first test aircraft flew just once, on a rainy night that fall, in the Pasadena Rose Bowl parking lot. Regular weekend tests at Mojave then began, resulting in a 40-second flight (Figure 7) by Parker MacCready on 26 December and a 2-1/2-minute flight by Greg Miller, a champion cyclist, in January 1977. Because of the expected high incidence of springtime winds at Mojave, in March 1977 the operation moved to Shafter, near Bakersfield in California's central valley. Here, the project acquired important additional assets: longer spells of calm air, a huge hangar, and skilled and devoted people living nearby, including Vern and Maude Oldershaw, Sam Duran, Bryan Allen, and FAI observer Bill Richardson. A redesigned aircraft (Figure 8) first flew at Shafter in March. Greg Miller soon made a five-minute flight, and on 23 August Allen made the prize-winning circuit of the Kremer course. Some recreational flying by all hands and by many visitors, as well as a little more development work, followed and then the Gossamer Condor was dismantled, hauled to Washington, D.C., and reassembled in the National Air and Space Museum of the Smithsonian Institution, where it hangs today.

Design of the Gossamer Albatross began in October 1977 and experiments with its new structural materials and processes began at Kirke Leonard's shop, Gen-Mar, Inc., at Hermosa Beach early in 1978. The airplane first flew at Shafter in July 1978. Early in 1979 we were able to lease an abandoned seaplane hangar at Reeves Field on Terminal Island in the Port of Los Angeles, where over-water testing and limited land testing could be done. Boats were obtained and prepared for the proposed over-water flights, and construction of three airplanes began. Sterling Stoll was the project manager for this phase and for operations in England; Duran was manager of flight testing. The builders included Bill Watson, Taras Kiceniuk, Blaine Rawdon, Steve Elliott, Dave Saks, and Ted Ancona, plus others recruited from the Southern California hang-gliding fraternity.

MacCready had at once realized that the Channel venture would require a much greater effort than the Gossamer Condor team by itself could support. Though the single objective was again just to win the prize, this time we would have to cope with many other factors. First, pilot safety and water rescue became paramount considerations. Second, the primary and back-up airplanes had to be made portable so that they could be taken to England, test-flown there over land, then transported to and quickly assembled at some launch site on the English coast. Third, navigation and communications had to be provided so that the airplane and its escorts could take the shortest possible air path from England to France while avoiding the Channel's heavy ship traffic. And finally a multitude of other details had to be arranged: test sites, physiological training, crew logistics and so on. Obviously these demands would exceed the team's private resources, so MacCready sought industrial sponsorship. In March 1979, the Du Pont Company, the source of the airplane's Mylar skin, Kevlar tension members, Delrin control parts and other resins and adhesives, agreed to be the chief sponsor and soon thereafter other sponsors, including Mercury engines and Zodiac inflatable boats for the rescue fleet, Polaroid for the sonar altimeter, and a number of private individuals for various support items, were enlisted. Du Pont provided not only funding but also important technical, logistic, and public-information support for the Albatross project. The company's interest in our later developments is continuing.

The key event in the Channel preparations was a long-duration flight. Late in April 1979, after some short test hops over the runways of Reeves Field (Figure 9), the Albatross was placed in its huge trailer (we built three of these to English road standards) and hauled to Harper Dry Lake in the Mojave desert, where Bryan Allen flew it for 18 minutes with one propeller and then for an hour and nine minutes with another, landing after this flight, not because of fatigue, but to permit another pilot, Kirk Giboney, to fly.

The Albatross did not then return from Harper Lake to Terminal Island. In a way that seemed at the time to be magic, with the aid of test pilots and RAF authorities whom we never met, transport to England had been arranged for the very next day in an RAF Hercules transport that was calling at Nellis AFB near Las Vegas. We brought the Albatross from Harper Lake, and the backup aircraft and other equipment, including engines and inflatable boats, from Terminal Island to Nellis where the RAF C-130 was loaded with all that it could take; some residual items were then shipped by commercial air to England. The three big trailers had to be left behind.

By the first week of May the operation was set up in a hangar at RAF Manston, Kent. How this happened is a story in itself -- suffice it to say that the British sporting spirit contributed not only the challenge and the prize itself, but hundreds of other indispensable items of support and assistance during the attempt. In both England and France, lasting friendships were formed as the preparations went forward. The contest conditions required supervised overland test flights; these were completed at Manston on 10 May. Then, after some weeks of further preparation, nautical rehearsals and waiting for weather, the number one airplane was moved on 10 June to the Warren, a British Rail maintenance site at the foot of the sea cliffs between Folkestone and Dover. Then at 0551 on 12 June, Bryan Allen took off, and at 0840 he landed on the beach at Cap Gris Nez in France.

This chronology makes it clear that both the Condor and the Albatross projects were done at a fast pace despite the fact that everybody worked only part-time up to the start of the Channel-crossing preparations. The bold decision to forego any over-water testing from Terminal Island in order to grab the proferred C-130 ride to England was typical: it reduced our chances of practicing and of knowing some operational details, but it increased our chances of being ready during the short period (late May and early June) when the Channel weather was likely to be calm -- a much more important constraint. Thus, in their own way, these projects demonstrated again an attribute that one recalls from the best-remembered projects in other fields: they had tight schedules which enforced a certain simplicity and a concentration on essentials, and each was characterized by a clearly-stated, unchanging goal and use of the simplest available means to achieve it.

4. AIRPLANE PERFORMANCE AND AERODYNAMIC DESIGN

4.1 POWER AVAILABLE

Human muscles convert chemical energy into mechanical work by a process whose details are just beginning to be understood (References 11 and 12). For our present purpose it is enough to note the end result: humans possess a very strong sprint capability and also a lower-powered, long-haul capability. Anyone who can run up a flight of stairs is putting out about one horsepower for a few seconds, and a strong athlete can double this output with no ill effects. The sprint, however, cannot be sustained. For the long pull a different mechanism takes over. Aerobic exercise, universally recommended for maintaining fitness, involves the continuous resupply of oxygen to muscles by the blood, with only a slow buildup of fatigue. An experienced hiker can put out almost 0.1 hp continuously; even a non-athlete typically has half this amount available and so can climb out of the Grand Canyon in daylight, with some rests along the way and no great misery afterwards. We thus can imagine the general character of a human power-versus-time curve: one to two horsepower at the origin, dropping down by an order of magnitude toward an asymptote. Figure 10, taken from Reference 2, shows various test results and is typical of the measurements on which most human-powered airplane designs have been based.

In the Condor and Albatross projects we were fortunate to be near a center of expertise in exercise physiology and muscle-driven machinery. At the Long Beach campus of California State University, Dr. Chester Kyle, Dr. Joseph Mastropaolo, and their associates, had for several years been doing research on human power output and man-powered ground vehicles. An annual speed contest and other competitions were rapidly advancing the state-of-the-art, and test data and training advice were readily available.

Though the Kremer rules permitted any number of crew and some two-place aircraft had been built, we chose a single-place design for the Condor, knowing that even this would demand a very large hangar. Also, we elected to use only a bicycle-type mechanism. Though some of the ground vehicles made use of the additional power that could be extracted by using arm and torso muscles, we believed that the extra machinery needed would be self-defeating in an aircraft, and that the pilot's hands should be kept

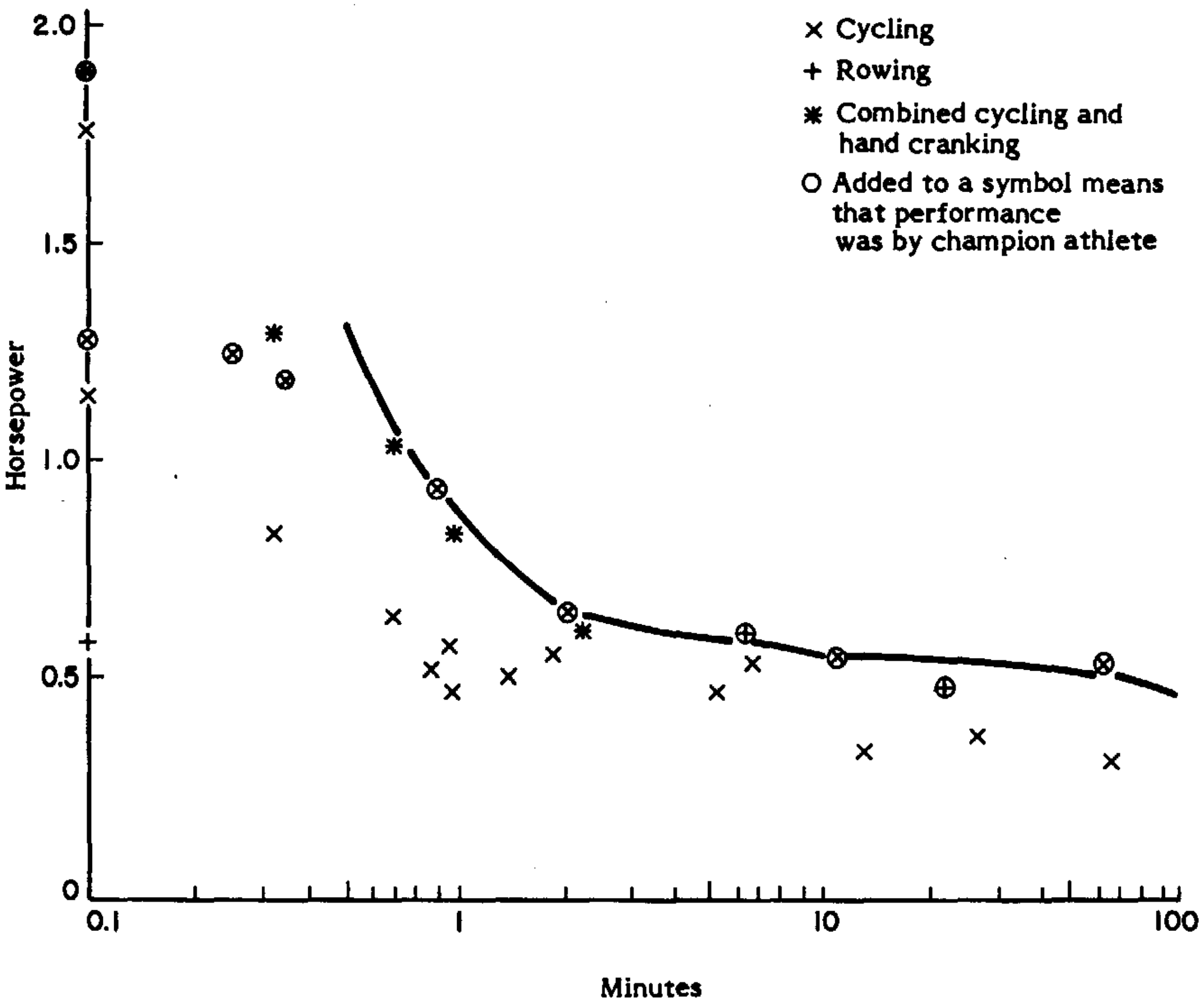

FIGURE 10. Human power output versus time.

free for manipulating the controls. Thus, the power available to the Condor was established as that of a single person, cycling. For takeoff and climb, this could be more than 0.5 hp, but for cruise it would be 0.4 hp or less. (Bryan Allen's actual performance, as measured by bicycle ergometer at the peak of his training for the Albatross venture, was in this range -- but the Channel flight called forth extra reserves of endurance that even he did not know he possessed.)

What made the Condor possible was MacCready's realization that there might be a region along the human power-versus-time curve giving more favorable power margins than those of previous contenders for the Kremer prize. Flying only half as fast, the airplane would take twice as long to complete the course, but if this resulted in, say, a 30% reduction in power required there would be a net gain. Let us now examine this compromise.

4.2 POWER REQUIRED

The power needed to sustain an airplane in steady level flight can be expressed (Reference 3) as follows:

$$P = \frac{2W^2K}{\rho\pi e b^2 U} + 1/2\rho U^3 A_1 \qquad (1)$$

where W = weight

U = speed

A_1 = equivalent flat-plate drag area

b = wing span

K = ground effect factor

e = span efficiency factor

ρ = air density

Equation (1) has many equivalent formulations. This one was chosen because, at this stage, it avoids complexities such as aspect ratio and lift coefficient, and emphasizes the fundamental dependence of power on weight, span, speed, and drag. The first, induced-drag term shows the importance of light weight and large span; the second term suggests that some parasite-drag-producing elements can be tolerated if the speed is slow enough.

The original Mojave Condor was designed to fly at about 8 mph. It had a wing span of 95 feet (to fit the available hangar) and a constant chord of a little less than 12 feet (tubing comes in 12-foot lengths). Assuming reasonable power train and propeller efficiencies, calculations showed that this airplane could have a good power margin at flight durations long enough to complete the Kremer course. It then remained to be seen whether or not such a huge, light, efficient craft could really be built. MacCready bought some aluminum tubing, Mylar, and piano wire and set to work.

4.3 AERODYNAMIC DESIGN EVOLUTION: STABILITY AND CONTROL

Trying the simplest possible solution first, Paul MacCready, Jack Lambie, and Kirke Leonard built an 88-foot-span model using hang-glider principles: The two-inch tubular spar was at the leading edge and the wing was just a Mylar sail shaped by a few ribs and a trailing-edge wire. Spar bending loads were carried by flying and landing wires to a central mast and king post, respectively, and the wing's trailing edge was kept taut by wires going to a bowsprit, which also provided a place to mount a stabilizer -- hence the canard configuration. This aircraft was tested one night near the Rose Bowl in Pasadena, with the "pilot" running and holding the central mast with one arm and operating a pitch control line with the other. It demonstrated the Condor's aerodynamic and structural principles well enough to launch the project into its next phase: building and flying at the Mojave airport, a hundred miles to the north.

The first Mojave Condor wing, illustrated in Figure 7, had a single-surface airfoil designed by Peter Lissaman. This wing immediately proved to have many virtues; its faults became evident later. Because of the huge wing area, flight was possible at very low speeds (though with high drag) so that push takeoffs and assisted landings at a walk or trot were feasible. Stalling was never a problem because the drag rise at high lift coefficients would bring the airplane to earth before the wing could stall. Takeoffs both aided and unaided were soon to become routine, even though the landing gear was laughable: two tiny, hollow plastic wheels from a toy fire engine. Thus the Condor avoided a major problem of previous Kremer contestants: driving a bicycle wheel for takeoff acceleration, carrying the associated weight during flight, and collapsing the wheel during hard or drifting landings.

The first main fault of the original Condor wing was its sensitivity to angle of attack. As in the case of a sail when operating above or below the design angle of attack, separated flow regions would develop near the leading edge. On a boat one watches the flow as shown by tufts and alters either heading or sail trim to correct this condition, but the Condor, even in seemingly still air, could not maintain a constant optimum angle-of-attack all across the giant wing, and so was subject to excess drag. We added a Mylar glove on the bottom of the wing from the spar back to about the quarter chord. This helped but, in view of other problems to be described below, we began thinking of a full two-surface airfoil for the next wing.

A second fault of the early wing was its lack of rigidity. The ribs were just bent tubes and they deformed badly in flight, trailing-edge tension could not be maintained until we added a rear spar, and the Mylar skin would billow into ugly bulges between the widely-spaced ribs. Despite all this, the wing worked well enough to permit many flights, and a thorough exploration of its third and most serious defect: nothing would make it turn.

The Kremer course requires two turns of more than 180 degrees, one to the left and one to the right. (As of early 1977, no human-powered aircraft had turned even 90 degrees; later that year the Japanese Stork did demonstrate a 180-degree turn.)

At the Condor's low speed the turns could be made with bank angles of only a few degrees. Because of the needed depth of the wire-braced structure, wingtip ground clearance was less of a problem than it had been for previous designs which had tried to take maximum advantage of aerodynamic ground effect. Thus, it seemed at the outset that we would be able to come up with some scheme for getting around the turns, so we concentrated, at first, on straight flights to work out the more basic problems of power available and required. The original craft had no vertical surfaces and almost no directional stability. If banked by a gust it would just slide sideways into the ground. We tried upper-surface spoilers, drag-producing ailerons, pendant rudders and, finally, a banking stabilizer for control, all the while accumulating more handling and flight experience and refining many aspects of the design but not solving the turn problem.

At length, as discussed in References 4 and 5, a combination of concentrated thinking, computer simulations, and model tests in air and water began to show the way to a solution: we would have to reduce the wingtip chord, using a tapered planform to reduce the anti-rolling effect of roll damping and of what is sometimes called apparent additional mass (References 14 and 15). When a wing is rolling steadily, a torque is opposing the roll, caused by the differing local angles of attack across the span. This is the familiar damping in roll, which must be overcome by the ailerons on an ordinary airplane. When a wing is accelerated in roll there is an additional opposing torque, due to the momentum that must be imparted to the air during the acceleration, which acts as if the wing had more mass and inertia than just that of its structure -- hence the term, apparent additional mass. For the very large and very light constant-chord wing of the Mojave Condor, these effects were relatively much more important than they are on conventional airplanes or sailplanes.

Though the Mojave airplane never made a successful 180° turn, it did begin to show signs of being controllable. It gave no evidence of being stable about any axis, but that did not seem to matter because all the motions were so slow. Parker and Tyler MacCready, both experienced hang-glider pilots, made many flights, and Greg Miller, a champion cyclist but not a pilot, quickly learned to use the controls correctly. Pitch control was entirely satisfactory, and some of the turn controls that we tried did have the desired effects, but only at an unacceptable cost in drag.

Yaw control via the banking stabilizer evolved from the familiar use of tilted stabilizers for trim of model airplanes. Fishline strings were attached to the stabilizer tips so that, in addition to the ordinary pitch control, the surface could be tilted. Since the stabilizer had lift, the tilted lift vector would lead the airplane around by the nose. An important aspect of the construction was that the bowsprit on which the stabilizer was mounted did not have to cope with any torsion, and so could be light. At last we had a turn control that almost worked, and it did so with no additional weight or drag. Afterwards, while we were congratulating MacCready on this brilliant stroke, he observed that soaring birds do essentially the same thing with their tails, and have been doing so for a long time.

Greg Miller did try the Kremer course at Mojave with FAI observers on hand, but the airplane was just not good enough and as the season advanced the calm spells when we could fly were becoming more infrequent, so it was decided to move to Shafter and the airplane was dismantled.

Peter Lissaman and Henry Jex, meanwhile, had been thinking and computing (References 5 and 6). Using his airfoil-design program, Peter produced a series of candidate sections from which the one illustrated in Figure 11 was selected for the next wing. The salient design criteria for this airfoil were as follows:

- Low drag over a good range of angles of attack.
- Low or moderate pitching-moment coefficients with little variation over the design angle-of-attack range.
- High lift-to-drag ratio at the low Reynolds numbers (~100,000 per foot) characteristic of these aircraft.
- A nearly flat bottom and moderate concavities for ease of construction and to keep the Mylar surface near the desired profile.

Achieving significant amounts of laminar flow was not a criterion because we believed this to be incompatible with the construction methods to be used. Also, obtaining high lift coefficients and predicting the wing's behavior at the stall were not then of much concern. When built, this airfoil proved to have excellent properties and it was used for the wing, stabilizer, and propeller blades of the next Condor.

With the airfoil selected, the remaining wing variables were planform and twist. Since the latter could easily be varied by adjusting the flying wires we did not specify it in advance. Henry Jex's dynamic modeling computations confirmed that the wing planform would have to be tapered to reduce the rolling reluctance that was due to roll damping and apparent additional mass. The spar was moved to about the quarter chord, the span increased to 96 feet (the Shafter hangar being much larger than the one at Mojave) and the wing was moderately swept to make it easier to put the airplane's center of gravity

All Values in Percent Chord		
x	upper surface	lower surface
0	0	0
1.25	2.25	-1.64
2.5	3.34	-2.01
5.0	4.96	-2.30
7.5	6.15	-2.30
10	7.06	-2.16
15	8.40	-1.70
20	9.26	-1.38
30	9.92	-1.06
40	8.97	-0.91
50	6.96	-0.75
60	4.86	-0.60
70	3.16	-0.45
80	1.81	-0.30
90	0.84	-0.16
95	0.41	-0.08
100	0	0

Nose radius 1.84, center of nose circle (1.84, 0.14)

Trailing edge angle from chord line
Upper surface 4.5°, Lower surface -0.9°

FIGURE 11. Lissaman 7769 Airfoil, used on both of the Kremer prize-winning airplanes.

where it belonged. The resulting wing is shown in Figure 8. Two were built, one with the 11%-thick airfoil of Figure 11 and another with an airfoil of the same family but 13.7% thick.

Because of the reduced area of the new wing, we knew that the airplane would have to fly a little faster, making the parasite drag a more important concern. Therefore a Mylar fairing was installed around the pilot. We had been prepared all along to do this if it should prove to be worthwhile from a weight-versus-drag standpoint, and it had not escaped our notice that such a fairing might create a favorable aerodynamic keel effect -- indeed, at one point during the Mojave testing we had installed a small triangle of Mylar aft of the king post for that purpose but had found no useful effect.

The Shafter version of the Gossamer Condor, shown in Figure 8, was completed about 2 March, and immediately flew well on its initial tests on 4 March. "Cruising" speed was 10 mph. Greg Miller soon made a 5-minute straight flight that was, at the time, an unofficial world duration record for human-powered aircraft. Turning, however, continued to be a problem. The banking stabilizer (now controlled by small servo ailerons to permit larger motions and require less control effort by the pilot) served well to initiate yaw, but could do little to provide rescue from a slip. We added a forward rudder under the stabilizer and we even tried a huge rudder aft of the propeller, as on the Wright Flyer, though we knew that the weight and drag of this cumbersome appendage would probably be unacceptable. After a somewhat more-than-routine crash caused by a divergent turn which the banking stabilizer could not overcome, we took the opportunity to clean up the airplane both aerodynamically and structurally, and sometime during this process the second and final turn-control breakthrough occurred.

Again this invention seems in retrospect to have been natural and inevitable. Why didn't we think of it sooner? Well, we just didn't. We did think of it early -- in fact, a number of the team members suggested it -- but without doing any calculations, MacCready assumed that our gentle 2^{o}-banked turns would not necessitate such a control. Eventually, he did some calculations which showed that considerable <u>reverse</u> wing-twisting (inside wing trailing edge down) would be the key. The concept seems to have arrived during or after a discussion of symmetric twist (wash-out or wash-in) as a means of improving the spanwise lift distribution (for minimum induced drag of the wing) and as a means of trimming the effective center of pressure of the swept wing so as to adjust the stabilizer load (for minimum induced drag of the wing plus stabilizer). These were important considerations but not nearly so critical as the turning problem. MacCready began calculating the angle-of-attack distribution required across the span with the wing established in a level turn; the dynamic pressure at the inner tip was only half of that at the outer tip, making it clear that the inner wing must have more incidence. Thus did the reverse twist originate.

It was simple to install a wing-twist control. A three-position lever under the pilot's seat was arranged to pull differentially on the outer flying wires, altering the incidence of the wing tips by about two degrees relative to the center section. With this control and the other minor refinements incorporated in the rebuilding after the crash, pilots immediately began making smooth coordinated turns. Not only did the twisted wing offer the correct spanwise lift distribution once established in the turn, it aided powerfully in starting the turn. Because of the airplane's peculiar combination of immense span and small yaw damping, when twist was applied -- for example, to start a left turn -- the left wing's higher drag ("adverse yaw" effect) would instantly yaw the craft to the left. Yaw-roll coupling would then cause a bank to the left, completely overcoming the ordinary aileron effect of the twist (which would initially tend to roll a more ordinary craft to the right) with the net result being a stable, gently banked, coordinated turn during which the pilot could make small turn corrections with the banking stabilizer, just as in straight and level flight.

This turn-control system, whose operation is probably aided by the slight wing sweep and the keel effect of the fairing around the pilot (both features that were initially added for other reasons) is the subject of one patent application emerging from the Gossamer Condor project (Reference 16). Henry Jex was able to simulate and understand its operation using his dynamical modeling program (Reference 5). The turns tend naturally to be quite well-coordinated, as confirmed by pilot observations of streamers on the stabilizer. As in the case of the banking stabilizer and the rocking tails of birds, an analogy with prior experience was soon evident: sailplane pilots almost unconsciously hold in a little top aileron while thermaling.

With the demonstration of satisfactory turns, aerodynamic development of the Condor was complete and only a minor clean-up for further drag reduction remained to be done before the prize-winning flight.

However, at this point it is well to note that success depended not only upon the fundamental advances just described but also upon a multitude of small increments in performance margin, eked out with care and diligence during the entire project. Many of these came under the heading of structures and will be described later. Some of them, however, were aerodynamic in nature. For example, there were the questions of how big the stabilizer should be and where it should be located ahead of the wing (we never considered an aft stabilizer because of the structural need for some sort of bowsprit). Computations and experiments with various stabilizers (including on one occasion, none -- to satisfy some of our flying-wing enthusiasts) led eventually to a compromise where the stabilizer area was 12% of the wing area, quite a bit larger than the minimum needed for pitch stability and control but giving a desirable increase in turn-control effectiveness and reducing the risk of stalling the stabilizer during sudden maneuvers. Building a collection of different stabilizers also refined our construction technique, and it gave us airfoil models that could be tested outdoors with tufts in moderate breezes, which was as close as we ever came to wind-tunnel testing.*

Stabilizer position was selected with some simple reasoning and a minimum of analysis. On the Mojave Condor it was straight ahead of the wing (Figure 7). For the Shafter machines we moved it down by drooping the bowsprit (Figures 1 and 8), hoping to get some induced-drag benefit from ground effect and also to get its wake away from the wing. For the Albatross it was moved back up again to reduce the parasite drag of the Albatross' longer bowsprit (Figure 2).

We put a lot of effort into detailed drag-reduction measures on the wing. From a sailmaker's viewpoint the Mojave wing was horrible: in flight the draft, or maximum camber, of the free Mylar surface would move aft from where it was intended to be and

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*A two-dimensional wind tunnel test of the Lissaman 7769 airfoil has since been made at MIT (Reference 17).

the ribs themselves would deform away from their intended profile. The Shafter wings, with their conventional airplane rib structures, were much better but even they were subject to a lot of distortion and billowing of unsupported Mylar. As one can see by studying the craft in the Smithsonian, the final Condor wing was a patchwork of attempts to control this problem with false ribs, extra pieces of tape, and so forth; the real and correct solution was made possible by the use of more advanced materials and techniques in the Albatross, whose closely-spaced ribs and tensilized Mylar skin gave a much smoother and more consistent surface profile.

One of the project's minor mysteries is the poor performance of the 13.7%-thick Condor wing. Since it was built after the 11% one, it was a bit smoother and better-looking, but its flight performance was definitely inferior. Neither theory nor observation tells us why. Since this project was solely directed toward the goal of winning the prize, there was no opportunity to explore the reasons for the problem; we merely put the old 11% wing back on.

The Albatross wing planform continued the evolutionary trend toward smaller chord, being designed to fly still a little faster -- 14 to 18 mph -- in the expectation that this would be more nearly optimum for a long flight, especially if headwinds were to arise. This higher speed, of course, produced a demand for further reductions in parasite drag, and these were achieved by many small, local improvements that can best be observed by closely examining and comparing the two museum airplanes.

In addition to general billowing and distortion, small fluttering motions of the Condor's Mylar were a frequent annoyance. The sounds could be heard by both pilot and crew, and the sounds always symbolized high drag. (The Albatross, in contrast, is almost completely silent.) Heat-shrinking could usually cure the problem, but sometimes so much shrinking was required that the surface would be distorted unacceptably. Reshrinking was required on occasion to cope with creep. We also tried air ducts to pressurize, equalize, or evacuate the wing to keep the surface taut and make it conform to the structure, but the results were inconclusive. A contrast of earlier and later constructions is shown in Figure 12.

One completely trouble-free aerodynamic feature of the Gossamer Condor and Albatross is the wing-fuselage intersection, a frequent source of problems in other designs. Tufts showed smoothly-attached flow in the wing-fuselage area under all flight conditions. Sometimes the fuselage skin would pump and shake a bit at the propeller blade frequency; moving the propeller aft was a simple and lightweight fix.

The presence of the bowsprit and canard stabilizer dictated a pusher propeller installation, which also permitted a simple and light drive train as described later below. The required depth of the wing bracing gave room for a large, slow-turning propeller, so all the propellers used had diameters in the region of 12 to 13 feet. Blade chord was chosen rather arbitrarily to provide plenty of area for absorbing high takeoff and climb power, and the Condor propellers (only two were made, being used without damage throughout hundreds of flights and many crashes -- another virtue of the pusher) had essentially constant chord, one of eight inches and one of ten inches. The blades were built with a twist distribution corresponding to some moderate rpm -- 100 to 120 -- and a forward speed of 10 to 14 mph, and were readily ground-adjustable in pitch. Variable gear ratios and in-flight pitch adjustment were regarded as impractical and unnecessary; the Condor props never gave aerodynamic trouble (with the possible exception of some momentary blade stalls during takeoff attempts by very strong pilots) and must have been fairly efficient, though we were never able to measure torque or thrust in flight. (We did, of course, measure rpm both by counting and with on-board instruments. Instrumentation is discussed later below.)

For the Albatross in its later stage of development, we took advantage of a more advanced propeller configuration. At MIT, Professor E. E. Larrabee and his students were developing propellers for their Chrysalis aircraft, a human-powered biplane that was built and successfully flown during 1978-1979. As described in Reference 18, Larrabee et al. had applied classical airscrew theory in detail to the problem of maximizing the efficiency of slow-moving propellers for motorgliders and human-powered airplanes, and had come up with a planform and twist giving near-ideal spanwise lift distribution and an overall maximum efficiency at the design condition. We selected the Eppler 193 airfoil, expected to perform well at low Reynolds numbers. The MIT team provided the complete design of a propeller optimized for the cruise condition of the Albatross; one was built at Terminal Island and, in the tests at Harper Lake, it proved to be notably superior in cruise to the original Albatross propeller (although much inferior for the takeoff condition). Thus, the MIT human-powered flying enthusiasts made a major contribution to the success of the Channel venture. In contrast to the constant-chord Condor and Albatross propellers, the MIT propeller has a complex and highly-tapered planform, as shown in Figure 2, with a maximum chord of ten inches and a tip chord of only about two inches.

Our final aerodynamics topic is the effort to reduce parasite drag, including cooling drag. Looking at the various Condor configurations, one can see the gradual trend toward more concern with this subject. On the original machine the equivalent flat-plate area of the wires, tubes, strings and other excrescences (including, at that stage, the pilot and drive machinery) was probably more than 8 square feet. Enclosing the pilot in a fuselage fairing probably reduced this by 20% and detailed clean-up may have contributed another 15%. Offsetting the beneficial effects of the fuselage fairing there arose, however, a need for fresh air for both respiration and cooling. The former was provided by a Mylar snorkel, which can be seen in Figure 1, directing air to the pilot's face and the latter was arranged for by means of inlet and outlet vents intended to cool the legs. As discussed in Reference 13, a human putting out flight power must reject a kilowatt or more of heat by sweat evaporation, and power drops at once if dehydration and overheating occur. For the 7-1/2-minute figure-eight flight this was an important consideration, but for the Channel flight it was vital, and the aerodynamic design tradeoff was difficult. In the end, Bryan Allen was provided with two liters of drinking water, a duct to carry away exhaled air, inlets and exhausts for body-cooling air, an aluminized-Mylar shade on the sunward fuselage side, and a vent that could be opened by pulling a string, giving some relief for overheating at the expense of additional drag. In the actual event, as described in Reference 7, these measures proved barely sufficient.

5. STRUCTURES

The whole reason for going to the original Condor's inelegant-looking configuration was to achieve minimum structural weight. Previous flyable human-powered aircraft had mostly weighed a hundred pounds or more -- some of them, much more. The power required for flight of a scaled set of similar airplanes varies inversely with the wing span and directly with the 3/2 power of the gross weight. With the pilot's weight more or less fixed, this says that the larger the machine can be for a given structure weight, the better, and also (because of the flatness of the human power-versus-time curve in the region of interest) that minor weight reductions can give large increases in available flight endurance.

Hang gliders have evolved an efficient structural concept using wire-braced tubes (somewhat resembling the masts and rigging of modern, high-performance sailboats) to support non-rigid airfoils. The early Condor was an extreme example of such a structure. The 95-foot spar was made from eight 12-foot lengths of 6061-T6 aluminum alloy tubing, 2 inches in diameter and chemically milled to wall thicknesses varying from 0.020 inches at the center to 0.015 inches at the tips. Each 12-foot spar section was designed as an Euler column with the conservative assumption of pinned ends; the spar proved able to endure great mistreatments without buckling. A vertical member at the center (we called the top part the king post and the bottom part the mast), made from the same sort of tubing, carried the landing and flying wires attached to the leading and trailing edges of each 12-foot bay along the wing, where there was a rib bent out of one-inch aluminum tubing. The wires were steel piano wire varying from 0.035-inch to 0.022-inch in diameter. Figure 13 shows how these wires were terminated and attached to the compression members. Nylon shoelaces provided quick attachment and easy adjustment of the multitude of wires to shape the wing. The wing was built upside down and then the airplane was taken out of the hangar and turned over in an operation that included weighing it. The original structure as shown in Figure 7 weighed 65 pounds including its 1200 square feet of 0.0005-inch Mylar skin.

The Mylar was attached to the spar, ribs, and trailing-edge wire using Mylar tapes with adhesive on one or both sides. Over the many months of the Condor and Albatross projects we used hundreds of rolls of these tapes -- a significant cost item.

This huge and absurdly flimsy-looking structure proved to be quite rugged once its idiosyncracies were understood. The tubular spar, mast, king post, bowsprit and propeller shaft took surprising amounts of punishment before buckling, often giving the impression of giant wet noodles in the sky, and when they did fail they were easily repaired by cutting out the crippled section and pop-riveting in a sleeve. The wires proved to be conservatively sized, seldom failing in pure tension but instead unwinding at their thimble-wrapped ends. For the Albatross, Paul McKibben devised an improved terminal resembling those used on antique airplanes, with the wire formed over an aluminum teardrop and then wrapped with a separate serving wire so as to develop more nearly the full strength of the main wire; these terminals proved very satsifactory.

The Mylar is an amazingly rugged material when used properly; dropped tools would bounce off the wing -- but its tear resistance is slight and any small cuts must be promptly taped to keep them from spreading. We used half-mil Mylar for the wing top surface and quarter-mil Mylar elsewhere at first, but the quarter-mil material proved annoyingly hard to work with and was often replaced by the heavier-gage film with but slight weight penalty.

To improve the lead angles of the flying and landing wires without increasing the mast and king post height, spreaders were installed at the 36-foot station of each Condor wing. These provided convenient handling points which aided in the prevention of crashes. To reduce parasite drag they were done away with on the Albatross and the outer 12 feet of each wing was braced by wires inside the airfoil, giving the appearance of a cantilever. Wire loads were calculated in a simple static fashion, assuming a reasonable spanwise lift distribution, and as mentioned earlier, the wires were quite trouble-free. As one index of the structure's ruggedness it can be noted that people were always running into the nearly-invisible wires, with the result being oaths and guffaws but usually no injury to either the person or the aircraft.

With the decision to abandon sails and go to a conventional two-surface wing, questions, of course, arose about the spar. With a wing nearly a foot deep at the root, it should in theory be possible to use a deep spar for shear and bending -- perhaps even to come up with some sort of torsion box and thus to eliminate a lot of the wires. Some tentative calculations and mockups in this direction were made, but they were soon abandoned because of the complexity and local fragility of any spar that could compete on a weight basis with the wire-braced, two-inch tube. Besides, we had the flight-proven spar tubing on hand; to build anything else would have delayed the whole project, and the parasite drag of the wires was not all that bad anyhow. (On the Gossamer Albatross we did reduce the number of wires, but they still aggregated more than 800 feet in length and on that clean an airplane they may have accounted for half of the equivalent flat-plate drag area. On the Condor, with its slower speed, the drag of the wires was less important.)

Having decided to stay with the two-inch tubular spar and to build conventional ribs (using 1/4-inch diameter, 0.010-inch wall aluminum tubing for the top and bottom with the same tubing, balsa wood rods, and glass-fiber strapping tape for the rib trusswork), we were left with the question of how to make the wing's leading edge. We experimented with heat-formed Styrofoam sheet, and this was successfully used for stabilizers, but for the wing we ended up with white corrugated paper of the kind that is used for party decorations. Because (unlike ordinary corrugated cardboard) this paper has only a single face sheet, it is easily formed into cylindrical or quasi-conical shapes, and Vern Oldershaw and his colleagues were able to create a good, stiff leading edge using a truss of balsa and Mylar adhesive tape along the aft side of a D-section of the corrugated paper.

The wing in the Smithsonian is thus a crazy patchwork of at least eight materials, even if three kinds of tape are counted as one, resulting from its evolutionary background. An index of Oldershaw's fine craftsmanship is that the prize-winning Condor, with all of its added features to improve control and performance, still weighed only 70 pounds -- less than most previous versions of the airplane.

The bowsprit and king post were sized and braced to cater to the expected stabilizer loads and wing and fuselage landing loads; the king post was quite trouble-free but the bowsprit, as might be expected, could easily be broken in handling or in crashes. As the bowsprit acquired more patches it may have been the source of our structural-design slogan: "If it doesn't break, it's too heavy." In any event, with handling experience the whole structure demonstrated quite adequate margins and probably could have been lightened a few percent more if needed. The mast of the Smithsonian airplane is another element with a lot of splints and patches. In addition to its role as the primary compression member in the wing bracing, this resists the chain tension between pedals and prop shaft (a load of 150 pounds or so) and it is subject to eccentric loads from the pilot, the control machinery, and the fuselage truss during landings. (The pilot's seat and the aft prop shaft bearing are suspended on wires from the wing and so do not directly load the mast.) We could have put in a much stronger and stiffer tube for the few ounces of weight of all the patches on the mast, but because of its central position in the structure this was not done.

The chain drive is another good, simple, trouble-free feature of these airplanes. Pedals, cranks and chainwheels are racing-bicycle hardware lightened by drilling additional holes, as permitted in the smooth and shock-free application of driving a propeller. The chain, which easily accommodates 90 degrees of twist between the pedals and the prop shaft, has the pitch of a standard bicycle chain but is made differently: it consists of little plastic aspirin pills molded into a structure that includes two 0.090-inch steel cables. This chain is a commercial product available from the Berg Company, Long Island, New York and is used for light-duty conveyors and other industrial applications. We worried about it, especially because every chain includes a swaged joint that eccentrically loads the cables but, in practice, chain failures were not a major problem. On the Condor the pilot reclined so that the loaded side of the chain could run straight between the sprockets. Tension of the slack side was maintained by a bungee-loaded idler. For the Albatross, pilot opinion and ergometer measurements showed that more power could be available with an erect cycling position of the pilot; to make this possible the chain was routed over two idlers, as shown in Figure 14, with no detectable loss of efficiency. This installation did, however, entail one of our few concessions to crash safety: a small shield was installed to keep the idler teeth from puncturing the pilot's chest in a crash. The top chainwheel was rigidly attached to the prop shaft, which assembly was mounted on a self-aligning bearing that transmitted thrust to the airplane. We would have loved to measure in-flight thrust at this point but we never found the extra man-hours needed to come up with a simple, reliable and precise way of measuring the small force (10 to 15 pounds) that made the airplane fly.

Extra-strong pilots could twist the propeller off the shaft until we added small gussets to prevent it, but the Condor's propeller shafts were quite trouble-free in spite of their mixture of torsion and bending loads. Propeller blades were retained by a slip-fit of

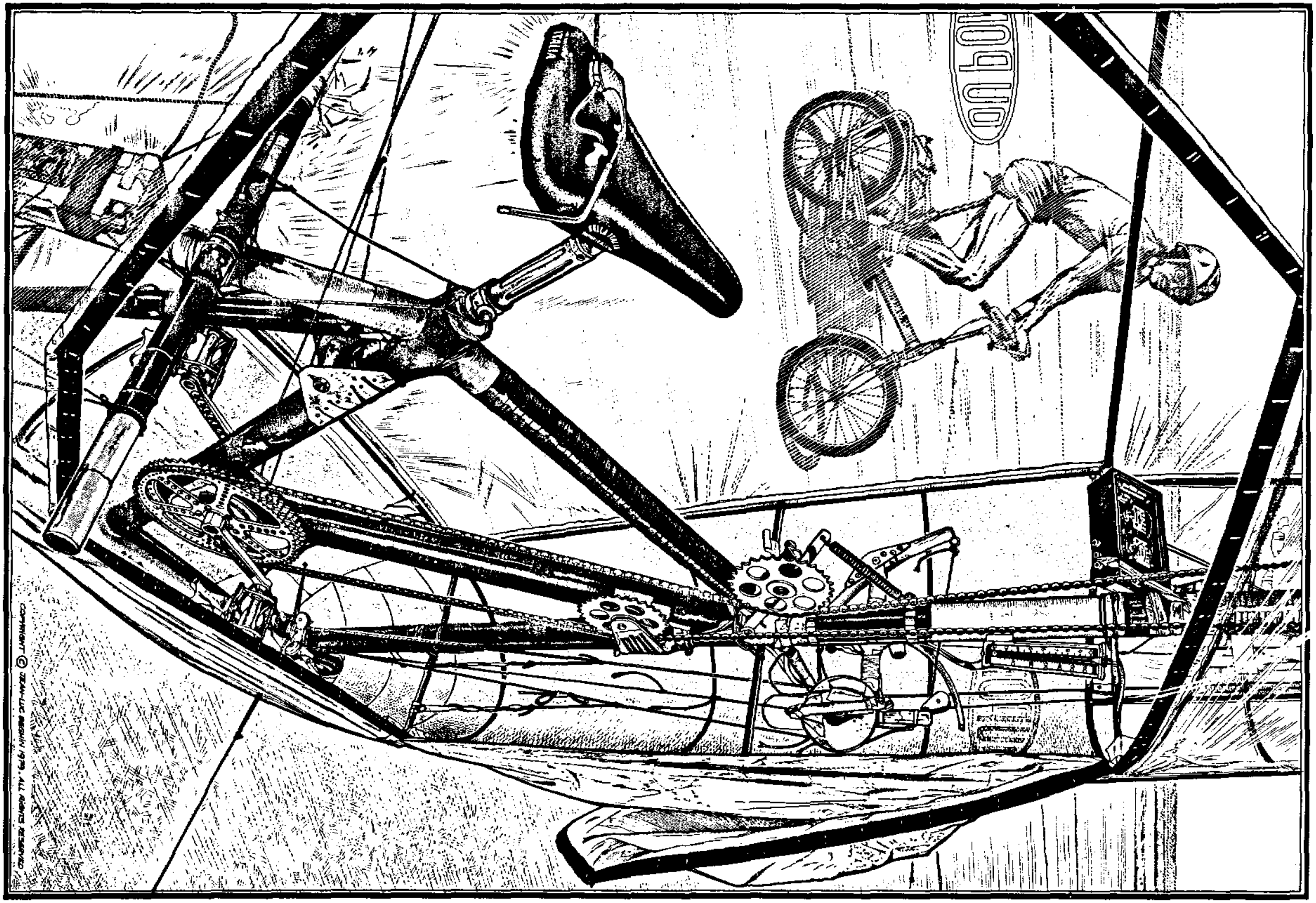

FIGURE 14. Interior of Gossamer Albatross fuselage. Drawing by Jean-Luc Beghin.

their tubular aluminum spars over hub stub spars, with hose clamps (also used elsewhere in the structure for various attachments) permitting easy pitch adjustment. The blades themselves were made by standard model-airplane techniques with balsa and Monokote.

Having described the Condor's structural evolution in some detail, we are now ready to take up the Gossamer Albatross. In its aerodynamics and control principles, the Albatross was just a slightly modified and cleaned-up Condor and its basic structural concept also remained unchanged, but in its materials, fabrication processes, and design details the Albatross was largely a new machine. The net effect of these changes can be seen in the reduction of empty weight from 70 to 55 pounds.

The general idea was to substitute carbon-epoxy composites for aluminum in the compression members and Kevlar for steel in the tension members, thus achieving a large weight reduction with no great changes in the structure's size, strength and rigidity. For the primary structure this was, in essence, done -- except that steel wires were retained in the external bracing. (They were changed to stainless, in deference to the marine environments of Terminal Island and the Channel.) At the wire ends, the Condor's nylon shoelaces were replaced by Kevlar. Secondary structures underwent much larger changes relative to the Condor. In particular much more use was made of expanded polystyrene (Styrofoam) in various thicknesses and densities, and multicomponent mixtures of materials were used to combine their various virtues. Figure 15 shows Albatross parts under construction.

The tubular spar sections were made by wrapping preimpregnated carbon-epoxy strips in helical layers on two-inch-diameter aluminum tubes, curing the composite in an oven, and then chemically etching out the aluminum. Styrofoam biscuits were then inserted to keep the tubing round, and in high-stress areas external Kevlar wrappings were added. Wing ribs were gang-cut from Styrofoam sheet (a process aided by the use of a constant 5-1/2-foot chord for the two inner 24-foot sections of the wing), carbon-epoxy cap strips were glued to the Styrofoam, and Kevlar threads wrapped around the assembly. The bond between carbon composite and Styrofoam (or, rather, the cohesion of the Styrofoam itself) was a weak point in such assemblies; under high local loads the carbon caps would pop away from the web. However, the great tolerance of the carbon to deformation would often prevent real damage to the cap strip, so that the failed area could be tied back down with Kevlar. As the builders became more familiar with the properties of these new materials a lot of detailed lore was evolved on how to use them in complex structures with a minimum of extra filler and adhesive weight, and a number of ingenious detail processes were developed which are self-explanatory when one looks at the airplane but would take a lot of words to describe. Fuselage formers, for example, with a cross-section of only 5/16-inch or so square, were cut from a dense blue foam, stripped with carbon and Kevlar-wrapped, yielding almost weightless airfoil-shaped hoops that were too strong: we ended up by slitting all of the Kevlar with a razor blade to enable the pilot to break them for emergency escape.

Propeller shaft failures did occur due to torsion-and-bending delamination of the helically-wound carbon fibre composite, on one occasion aggravated by absence of the required internal Styrofoam biscuits. This could have been cured with some more work on the shaft, but in the end we just went back to an aluminum tube, thus trading a few ounces of weight for simplicity.

Du Pont technical people gave invaluable assistance during this phase of the project, among other things recommending and supplying the tensilized Mylar that gives the Albatross wing its beautiful surface. This material has a unidirectional shrink property that makes it ideal for use on cylindrical structures, and, together with the close rib spacing made possible by the new lighter materials, it enabled super-light wings to be built with surface quality resembling that of sailplanes -- a far cry from the old Condor's bulgy and wrinkled skins.

One new structural problem had to be solved for the Albatross: portability. As mentioned in Section 3, we believed that quick preflight assembly, working out of a big trailer or at best a small shed, would be necessary at the coastal launch site in England. For safety and to rule out soaring, the Channel contest rules (Reference 19) required that the launch be from near sea level, and we doubted that an indoor assembly facility would be available. (In the actual event, British Rail did kindly provide us with a shed that could contain the parts but not an assembled airplane.)

The wing-fuselage connection was already quite suitable; the mast was just a slip fit over a stub fitting on the wing center section. The fuselage was therefore designed to be a self-contained assembly including the drive train and shaft. The prop shaft was provided with a pinned sleeve joint for quick installation of the propeller, cantilevered behind the rear shaft bearing which was now built into a strong foam-and-carbon box at the top of the fuselage. The wing was broken into four sections. At each end of these there was a rib box with enough spanwise rigidity to carry the skin tension. Assembling the wing then involved telescoping a short slip-fit section of spar at each joint, wiggling the wing fore and aft to permit insertion of pins at the leading and trailing edges, installing the king post, landing wires, and bowsprit, taping the joints, and then placing the wing atop the fuselage, after which the flying wires and Kevlar control cords could be connected and the stabilizer installed. The quick-disconnect devices that make these actions possible do look like something bent out of a paper clip, but they are carefully designed and made of high-strength wire. The assembly team led by Taras Kiceniuk developed accurate, fast and reliable methods for completing and checking the assembly steps, and at the Warren before the Channel takeoff (Figure 16) the airplane went together with no delay. And, despite all the stiff boxes and extra joints in the primary structure, because of the use of advanced materials and clever detailed design the excess weight chargeable to portability is at most a few pounds.

The new MIT propeller for the Albatross was also made differently: on a carbon-epoxy tube spar with added carbon caps, the airfoil was carved out of dense blue foam, covered with Kevlar cloth, sanded and painted. The resulting blades were a little heavier but much smoother and stiffer than those of the Condor props. At one point in the design process we had actually considered ballasting the propeller tips to obtain more constant instantaneous rpm, but later calculations showed that even fairly jerky rotation would cause no significant inefficiency. In any case the Kevlar-covered propeller did pedal very smoothly and its slight extra inertia may not have been all bad.

The appendix contains detailed drawings of both the Gossamer Condor and the Gossamer Albatross.

6. INSTRUMENTATION, NAVIGATION, AND AUXILIARY EQUIPMENT

This section will be mainly a summary because we did not attempt to improve the art of instrumenting low-and-slow flight; we merely used the minimum equipment considered necessary to learn what we needed to know. The flight instruments of the Condor included aluminized-Mylar yaw streamers on the stabilizer, reference lines on the windshield, and two bicycle-type meters, one driven by a magnetic pickup from the pedal chainwheel and one driven by the same kind of pickup from a small windmill mounted on the bowsprit. The airspeed measurement proved to be an important aid to both the pilot and the test crew. Pedal rpm proved unimportant and that instrument was seldom used; it was, anyhow, fairly easy to count propeller revolutions with a stopwatch while riding a bike behind the aircraft (the blades had different colors to facilitate this).

Tufts were, of course, an important aid in flow visualization for the ground observers and were used throughout the program, but they were of little importance to the pilot. Other ground instrumentation included precision protractor levels (very important for checking propeller pitch and other angular relationships), ball-in-tube and rotating-cup anemometers, and a fish scale for towed drag tests. We used both the latter and timed glides to investigate lift-to-drag ratio and drag variation with speed, but in my opinion at least, the results were seldom useful and our most reliable performance indicator was the pilot's own knowledge of how much power he was producing, based on experience in riding an accurately-calibrated bicycle ergometer. Drag measurements with a fish scale were helpful in illuminating the drag penalty associated with wing control motion.

For the Gossamer Albatross venture the on-board equipment had to be more elaborate. The team included ex-Navy seaplane pilots who were familiar with the dangers of misjudging height above a calm water surface, so accurate altitude knowledge was recognized as a necessity. Two ways of observing altitude were considered feasible and both were used. The pilot was provided with an acoustic altimeter adapted for us by Polaroid from their automatic-focusing Polaroid camera, with the tiny transducer located at the bottom aft tip of the fuselage fairing. This altimeter worked precisely and excellently in tests, and it was backed up by altitude callouts from the accompanying observers.

Cross-Channel navigation was the next problem to be considered, and it contained some subtleties. The central objective was to achieve a least-time air path at a near-optimum cruising speed considering both the power-required properties of the airplane and the power-available properties of the engine. We knew that we would have to go during a (probably short) interval of calm wind, and that this would make it impossible to specify the state of the tide at flight time -- in all probability, as described in Reference 20, the water would be flowing rapidly one way or the other across our path and dragging the air with it. To make the pilot figure all this out and take up a best heading, in addition to his other chores, was plainly ridiculous and therefore there was never any thought of putting a compass in the airplane. We decided that the only practical option would be to instruct him simply to follow a boat, and to put all of the navigational planning and knowledge in that boat. Because calm winds in the Channel often coincide with restricted visibility, the boat would have to have radar -- both to show landmarks for precise path planning in the presence of the expected tidal cross-currents and to enable ship avoidance.

The shipping problem was serious. Hundreds of large vessels transit the Channel every day, supposedly under rigorous control in two main traffic lanes, and there is also much cross-lane and random traffic. (Two collisions with loss of life occurred during our preparatory stay in England.) For the Albatross the problem was not just to avoid hitting a ship; for miles downwind of a big vessel there is an air wake that might instantly bring our airplane down, hence must be avoided even if we had to circle in mid-Channel.

During the weeks of preparation much mental energy and many words were spent on this problem and its associated vector diagrams. During the flight, with the aid of both British and French Coast Guard radar stations, the skilled British yachtsmen, John Ward, Frank Booton, and John Groat, who, with Paul MacCready and his sons Parker and Tyler, manned the lead boat, Lady Ellen Elizabeth, led us across with only one significant course deviation to avoid the air wake of a tanker. The lead boat was backed up by another motor yacht, the Tartan Gem, and by dead-reckoning and piloting equipment and an experienced ocean navigator in one of the inflatable rescue boats.

Finally there was radio. Opinions were mixed about this, but in the end the airplane was provided with the electronic insides of a hand-held VHF transceiver and Bryan Allen wore a featherweight headset along with his shoes, shorts, float unit, glasses and helmet.

Surprisingly, given all of the circumstances, most of the aircraft's electronics worked well during their design or battery lifetimes, but because of the excess flight time due to an abortive takeoff and then to a headwind, all but the radio receiver became inoperable long before the landing in France; the last five miles or so were done in the backup mode which relied on piloting skill, without instruments, but with radioed information.

7. THE NET RESULT

The final power margin of the Gossamer Albatross was extremely small. With the excess air turbulence and the weight of instruments, drinking water, and safety equipment, plus about three pounds of dew (which did not noticeably evaporate off the wing during the crossing) giving a takeoff gross weight of 215 pounds the power margin was small, even for a two-hour crossing. The turbulence greatly increased the power demand and the headwind that came up halfway across added almost another whole hour to the time of flight.

Our final aerodynamic discovery was made by Bryan Allen on 12 June 1979 about six miles northwest of Cap Gris Nez: Bryan, sensing that he could not go on in the turbulence just above the waves, signaled to Sam Duran for a tow. He climbed to ten or fifteen feet; we got under him (Figure 17) and Bill Watson was about to attempt a hookup (a planned but never practiced maneuver) when Bryan shouted down that he wanted to try it up there for a while. Though the beneficial aerodynamic ground effect was less at the higher altitude, the wave-and current-induced air turbulence was much less, giving a net reduction in power required. We had planned the flight for May-June because during this period a few days of very light winds are common and the water is typically considerably colder than the air. This stable temperature situation can be expected to cause surface-induced turbulent motions to decrease with height. The low altitude turbulence turned out to be stronger than expected (we had hoped for lighter winds), but the decrease with altitude was also more pronounced than expected. With this discovery of smoother air giving both body and spirits a lift, Allen, using incredible determination plus reserves that even he did not know he possessed, made it all the way to the beach at Cap Gris Nez (Figure 18) and was happily partying in Paris a day and a half later. It was a very close-run thing; Bryan feels he could not have gone even 300 feet further than he did. Every tiny increment in performance margin, due either to new fundamental insights or to meticulously detailed work over the months of design, building, and preparing the Gossamer Albatross, was essential to its success.

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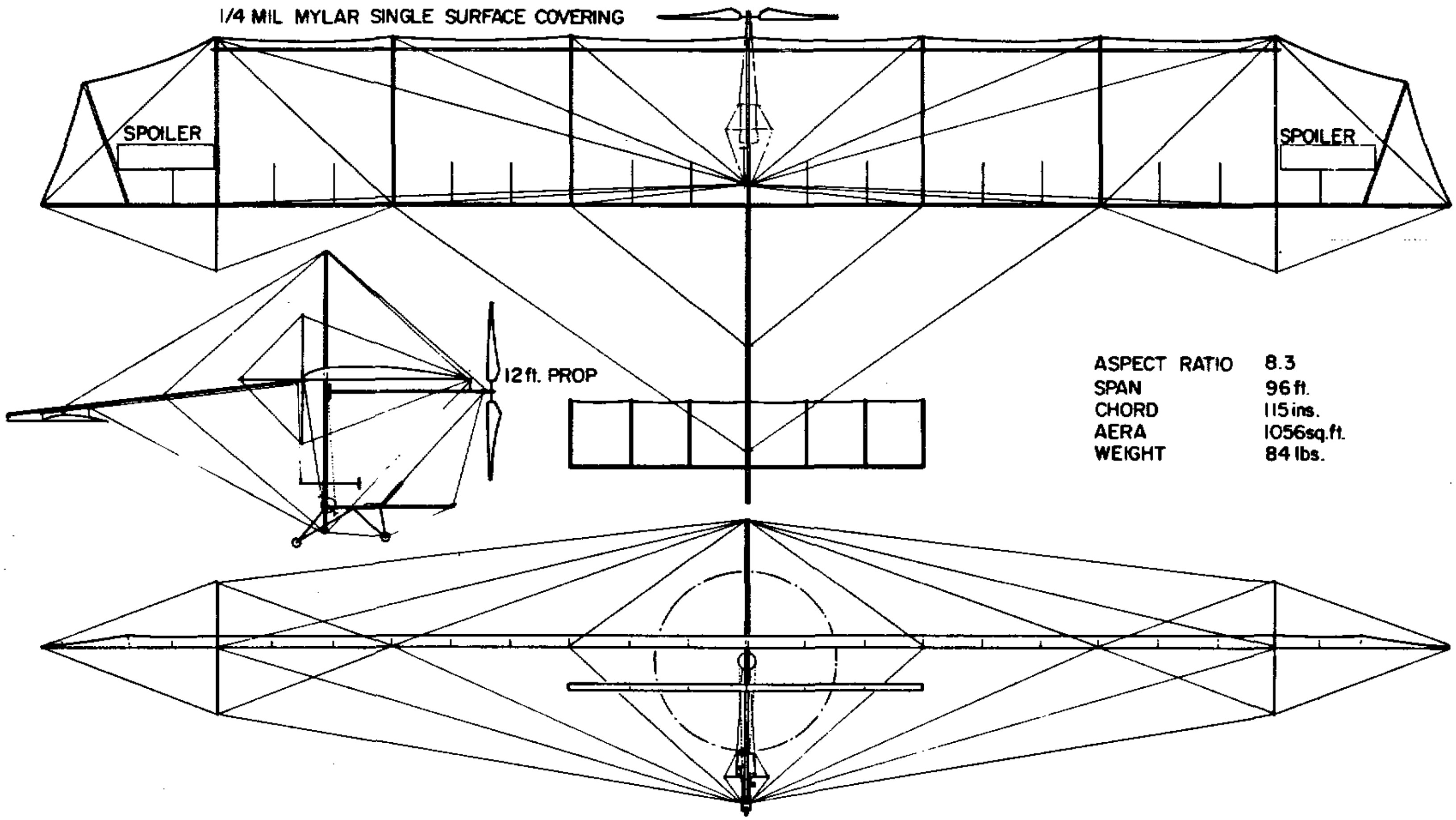
APPENDIX

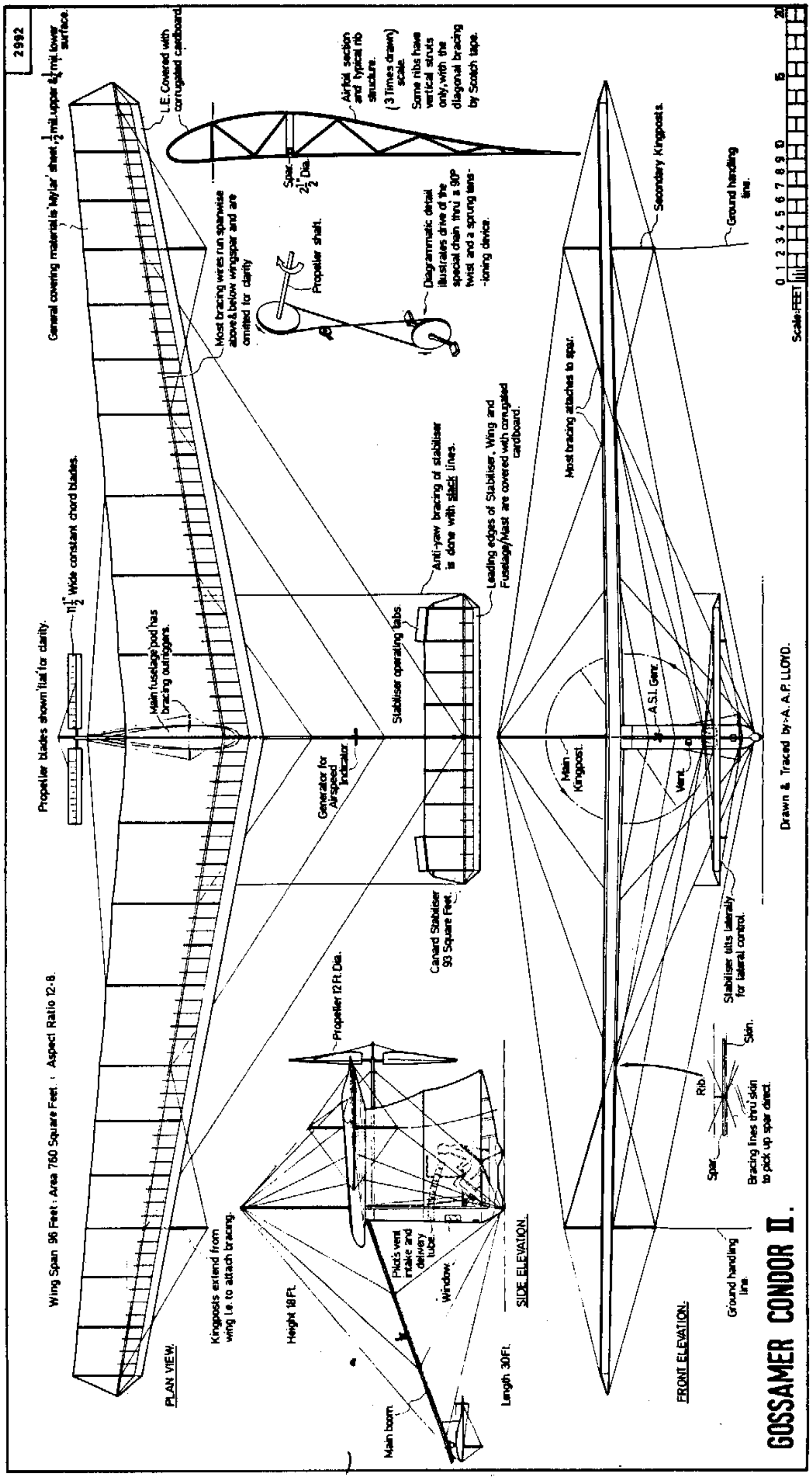
Detailed Drawings of Gossamer Condor and Gossamer Albatross

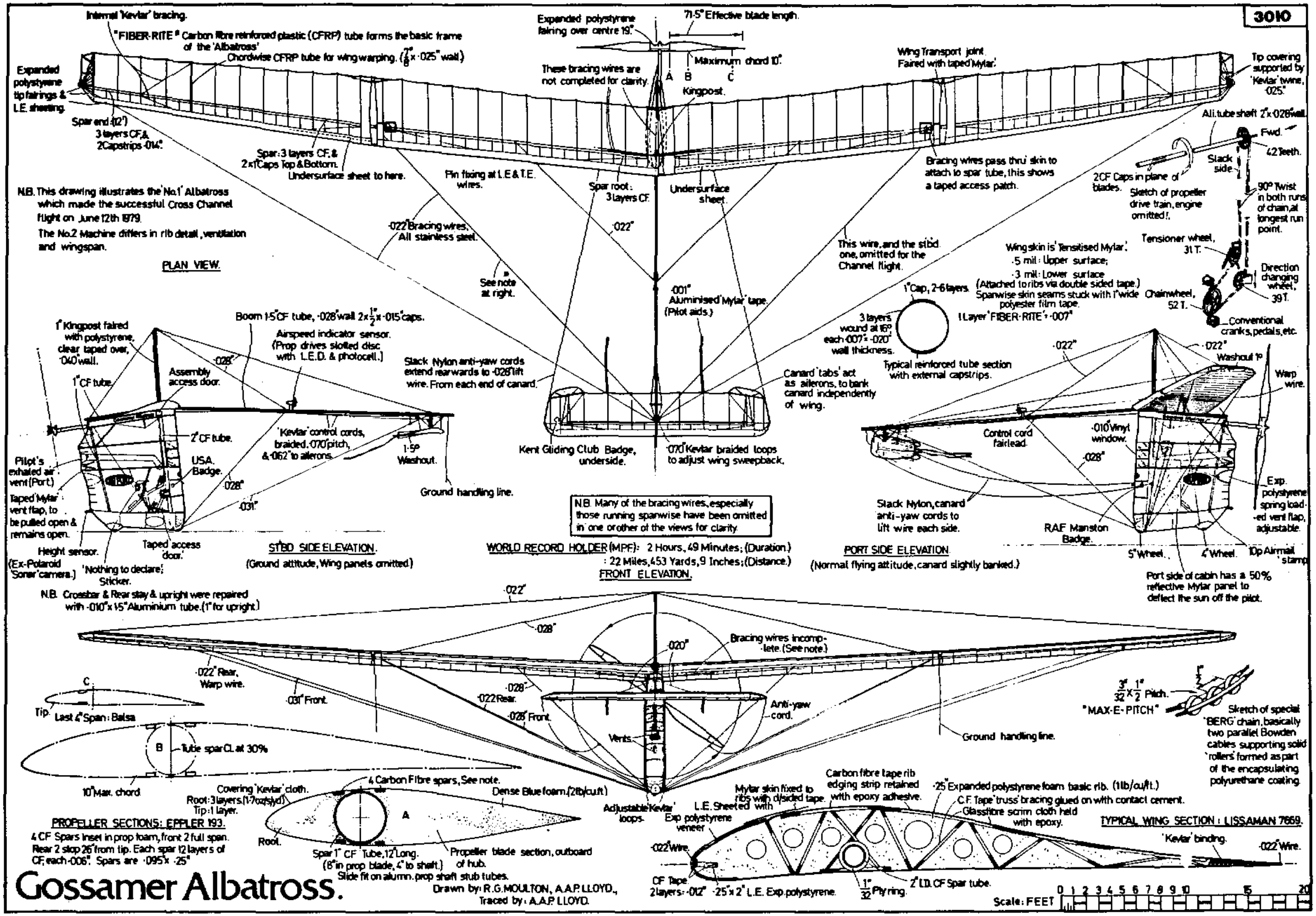
The drawings in this appendix are by Pat Lloyd, © Aeromodeller magazine, England, and have been kindly supplied by Ron Moulton of Model & Allied Publications Ltd. Moulton accompanied the Channel crossing as a designated FAI observer and his account of the venture (Reference 10) is a concise and well-illustrated description of the event.



ASPECT RATIO	8.3
SPAN	96 ft.
CHORD	115 ins.
AERA	1056 sq. ft.
WEIGHT	84 lbs.

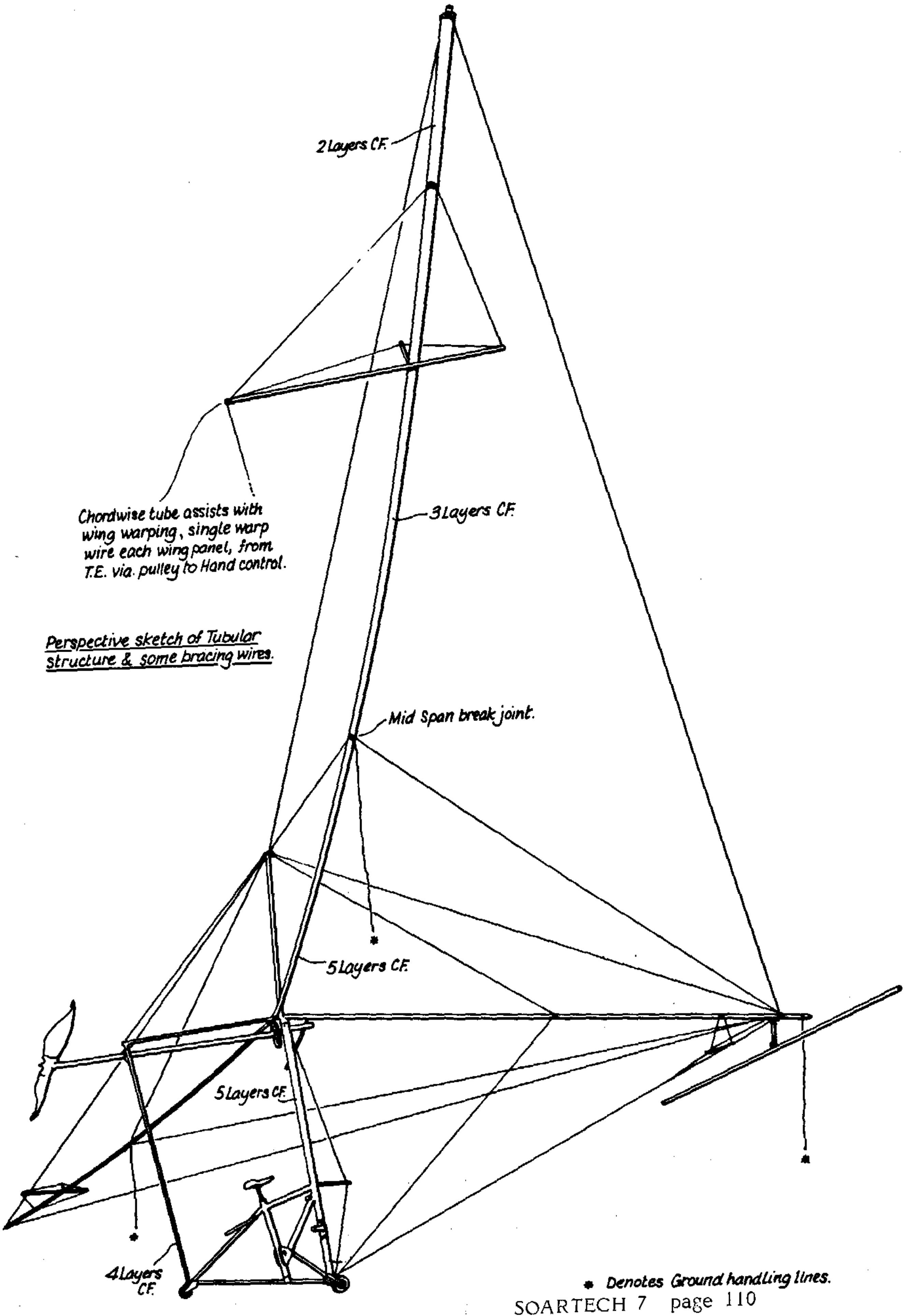
GOSSAMER CONDOR I (Mojave version.) 332 FLIGHTS


2992
General covering material is 'Mylar' sheet 1/2 mil upper & 1/4 mil lower surface.
L.E. Covered with corrugated cardboard.
Airfoil section and typical rib structure. (3 Times drawn) scale.
Some ribs have vertical struts only, with the diagonal bracing by Scotch tape.
Spar 2 1/2" Dia.
Most bracing wires run spanwise above & below wingspar and are omitted for clarity
Propeller shaft.
Diagrammatic detail illustrates drive of the special chain thru a 90° twist and a sprung tensioning device.
Secondary Kingposts.
Ground handling line.
Scale: FEET 0 1 2 3 4 5 6 7 8 9 10 15 20
Propeller blades shown 'flat' for clarity.
11 1/2" Wide constant chord blades.
Main fuselage pod has bracing outriggers.
Generator for Airspeed Indicator.
Stabiliser operating tabs.
Anti-yaw bracing of stabiliser is done with slack lines.
Leading edges of Stabiliser, Wing and Fuselage/Mast are covered with corrugated cardboard.
Most bracing attaches to spar.
A.S.I. Genr.
Main Kingpost.
Vent.
Drawn & Traced by:- A. A.P. LLOYD.
Canard Stabiliser 93 Square Feet.
Stabiliser tilts laterally for lateral control.
Wing Span 96 Feet : Area 750 Square Feet. Aspect Ratio 12·8.
Propeller 12 Ft. Dia.
Kingposts extend from wing l.e. to attach bracing.
Height 18 Ft.
Length 30 Ft.
Pilot's vent intake and delivery tube
Window.
SIDE ELEVATION.
PLAN VIEW.
Main boom.
Rib.
Skin.
Spar.
Bracing lines thru skin to pick up spar direct.
Ground handling line.
FRONT ELEVATION.
GOSSAMER CONDOR II.



Gossamer Albatross.

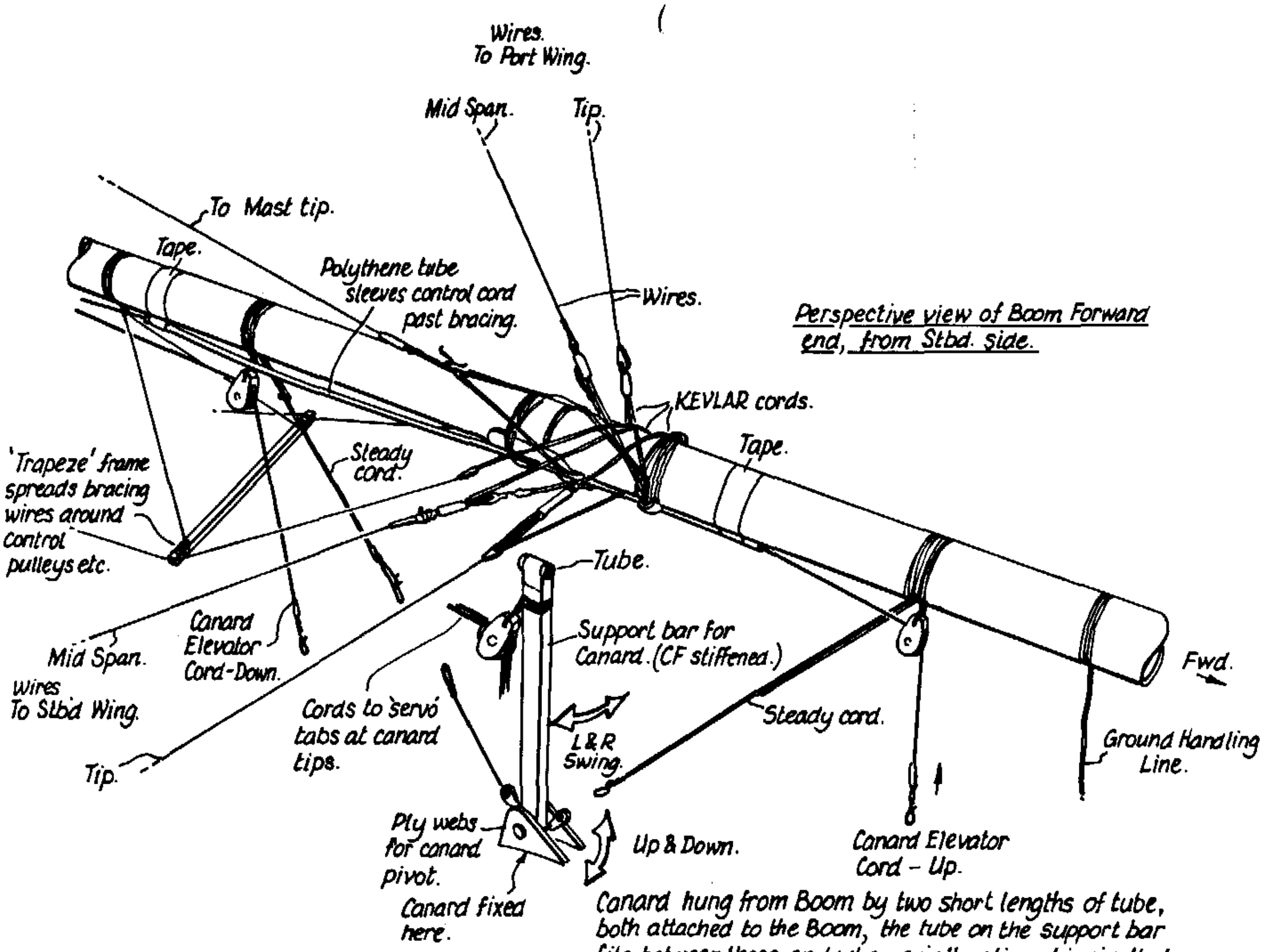
Drawn by: R.G. MOULTON, A.A.P. LLOYD.,
Traced by: A.A.P. LLOYD.



Perspective sketch of Tubular structure & some bracing wires.

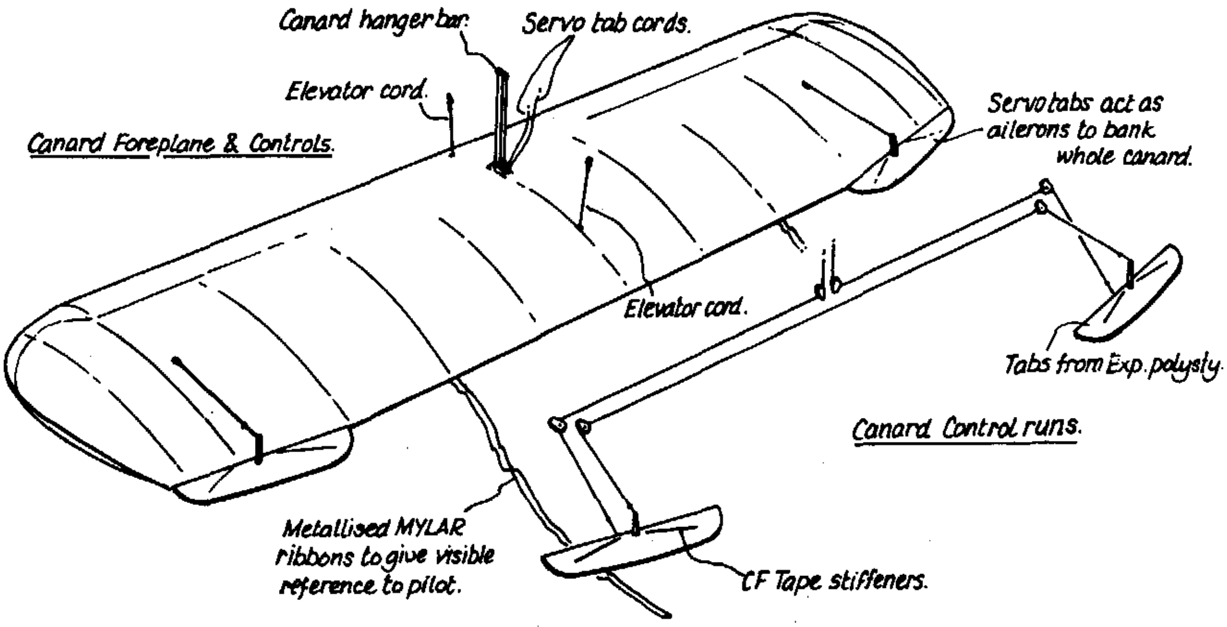
* Denotes Ground handling lines.

A A P LLOYD — '79.



Perspective view of Boom Forward end, from Stbd. side.

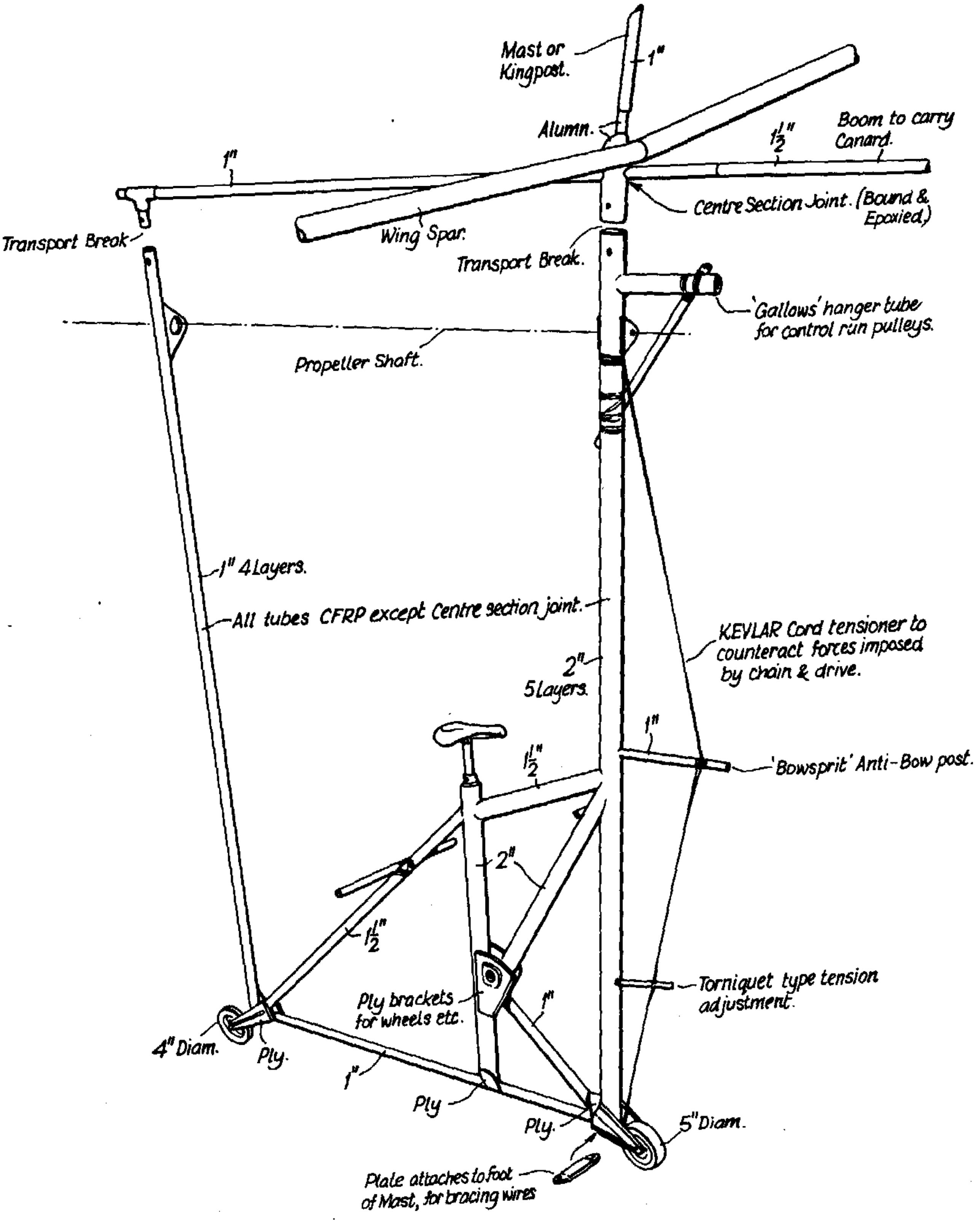
Canard hung from Boom by two short lengths of tube, both attached to the Boom, the tube on the support bar fits between these and when axially aligned is pivotted by a short rod.



Canard Foreplane & Controls.

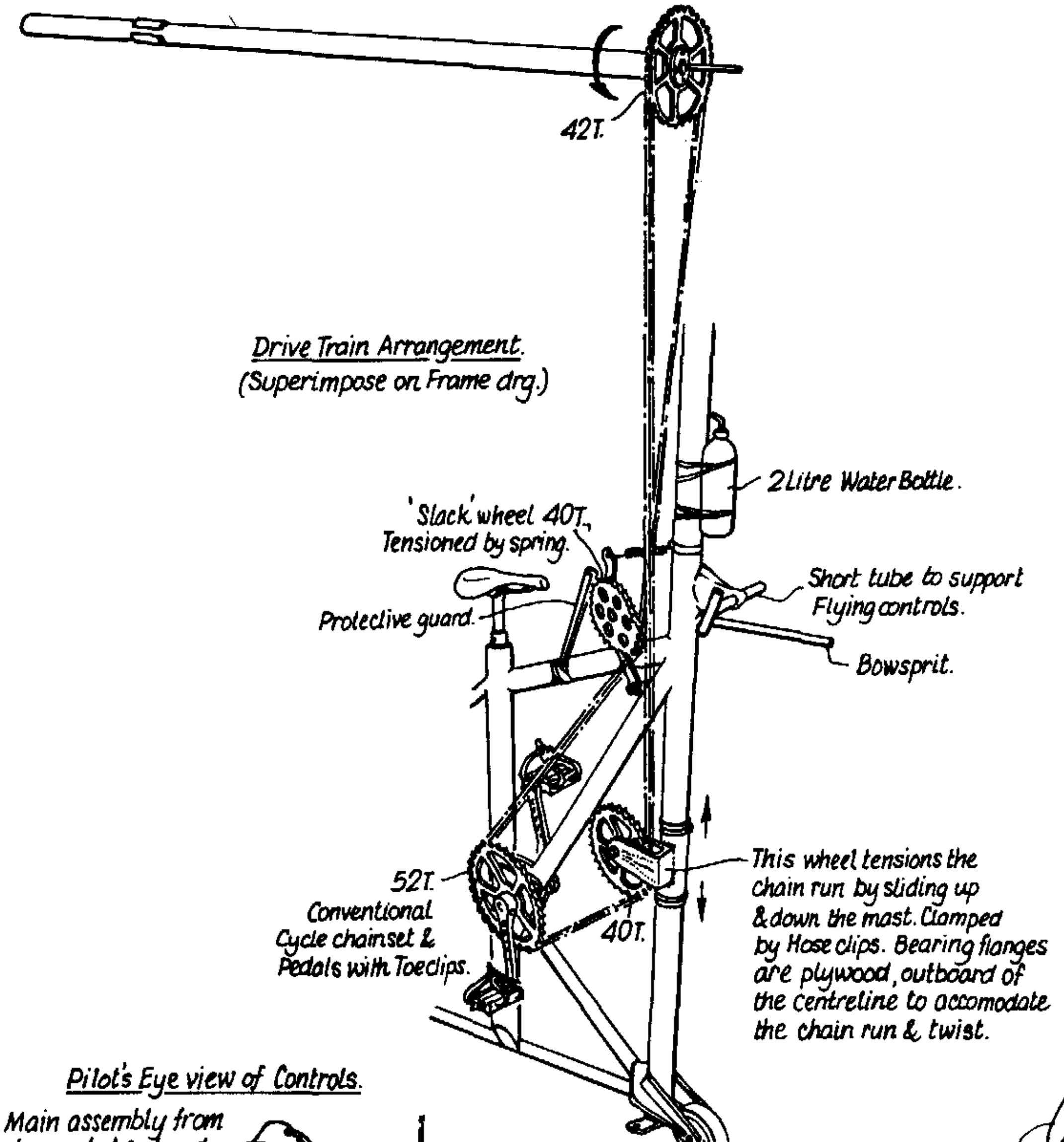
Canard Control runs.

AAPLLOYD '79.

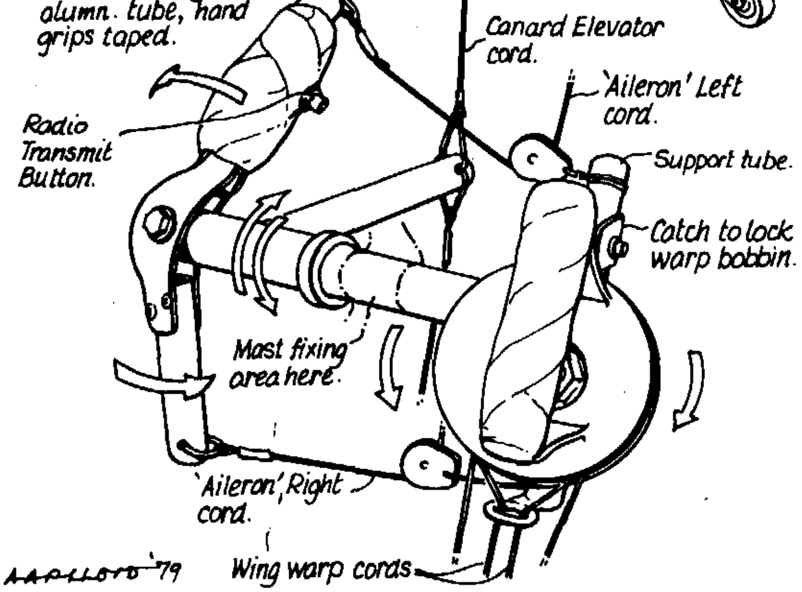


General Arrangement of Gondola Basic Structure & Attachment of Wing Unit.

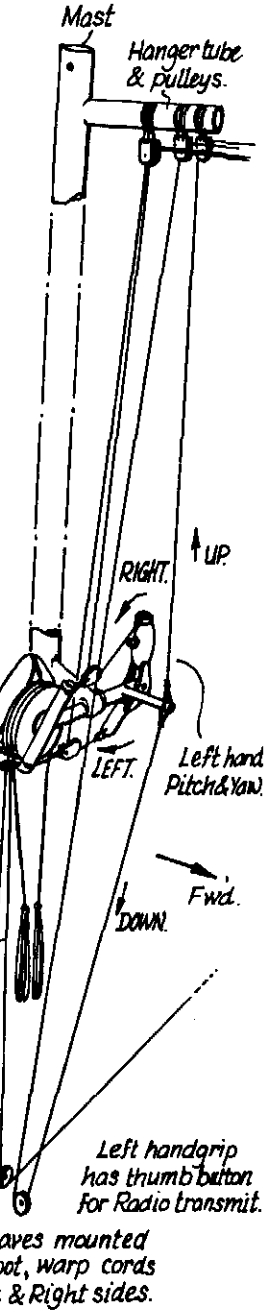
AAPLLORD '79.



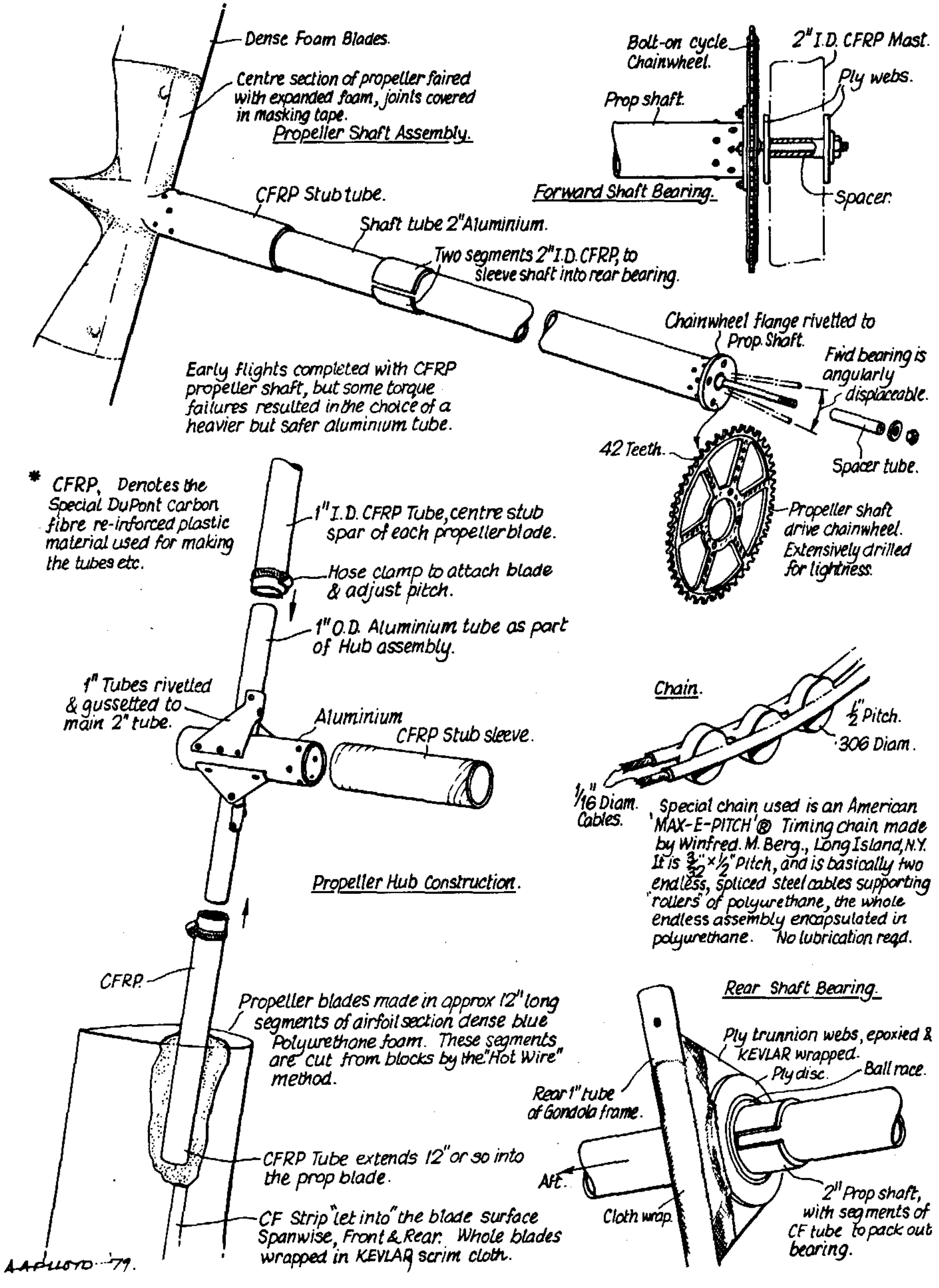
Drive Train Arrangement.
(Superimpose on Frame drg.)



Pilot's Eye view of Controls.



Fuselage mounting of Flying controls.

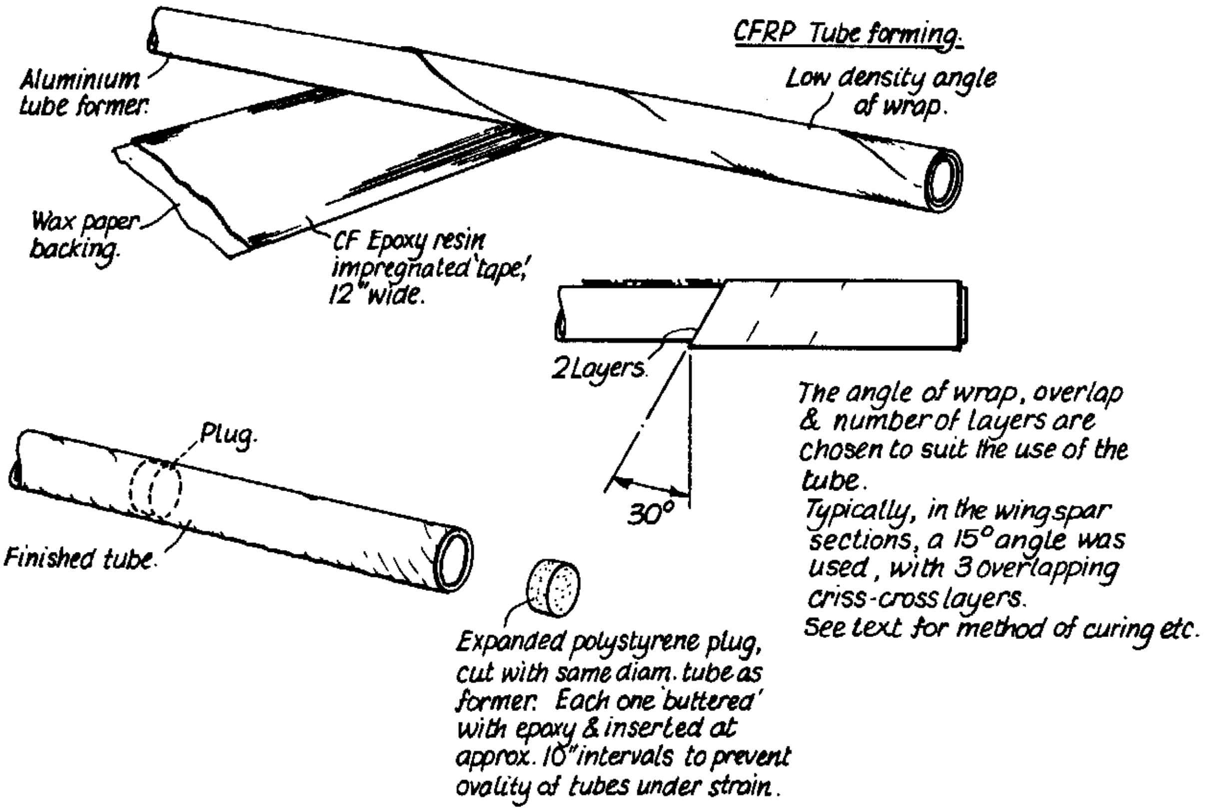


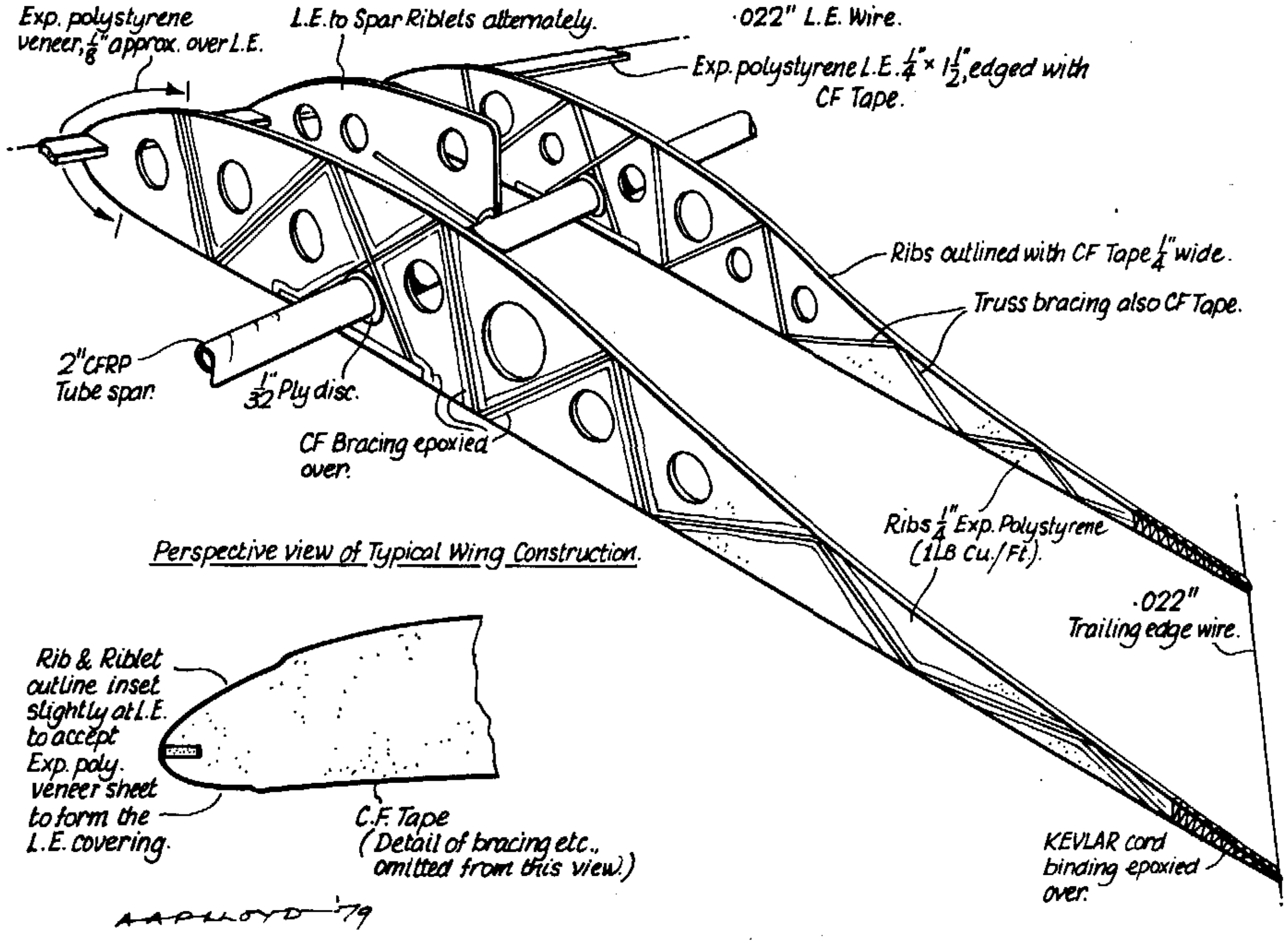
Early flights completed with CFRP propeller shaft, but some torque failures resulted in the choice of a heavier but safer aluminium tube.

* CFRP, Denotes the Special DuPont carbon fibre re-inforced plastic material used for making the tubes etc.

Special chain used is an American 'MAX-E-PITCH'® Timing chain made by Winfred. M. Berg., Long Island, N.Y. It is $\frac{3}{32}$"×$\frac{1}{2}$" Pitch, and is basically two endless, spliced steel cables supporting "rollers" of polyurethane, the whole endless assembly encapsulated in polyurethane. No lubrication reqd.

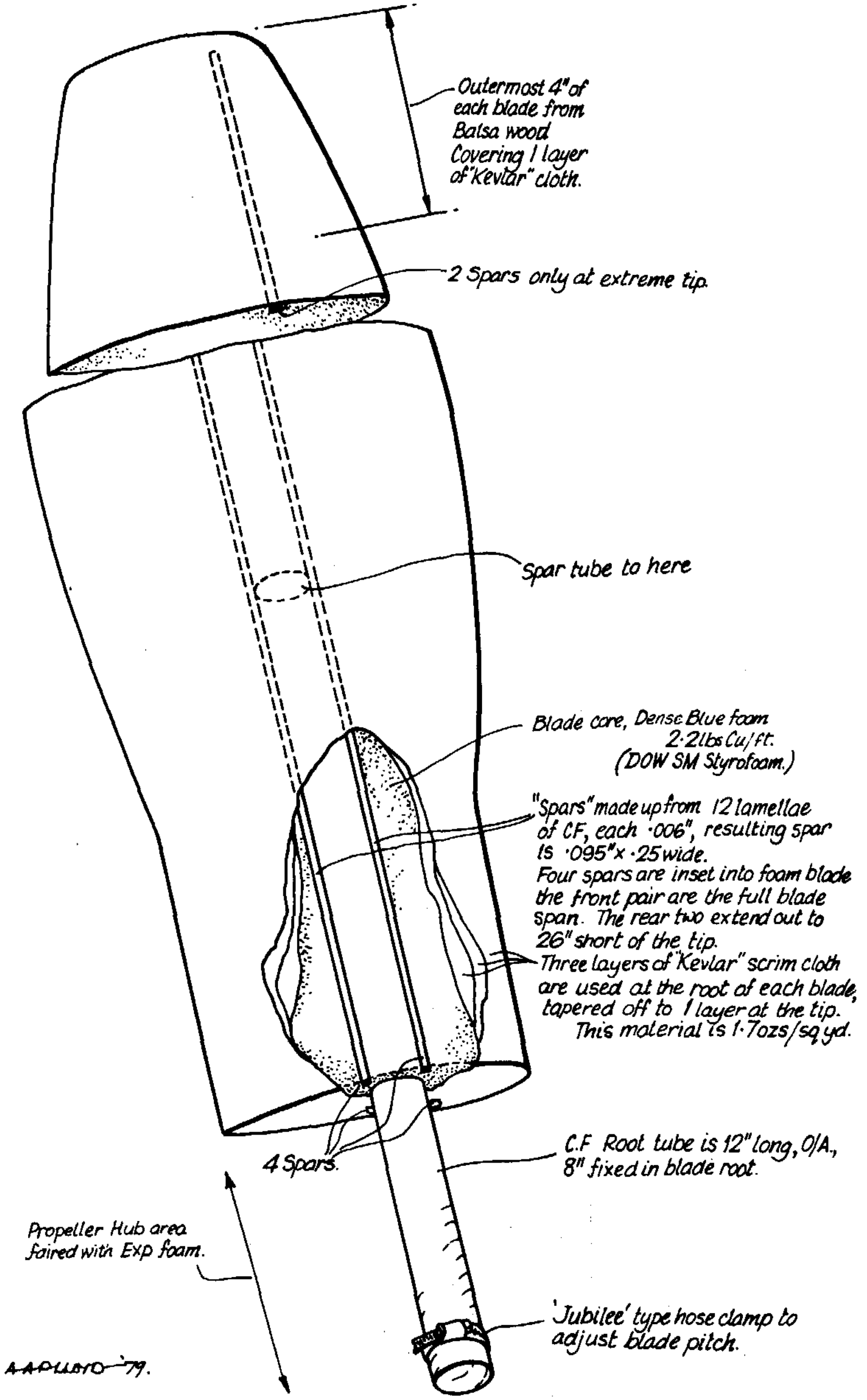
Propeller blades made in approx 12" long segments of airfoil section dense blue Polyurethane foam. These segments are cut from blocks by the "Hot Wire" method.

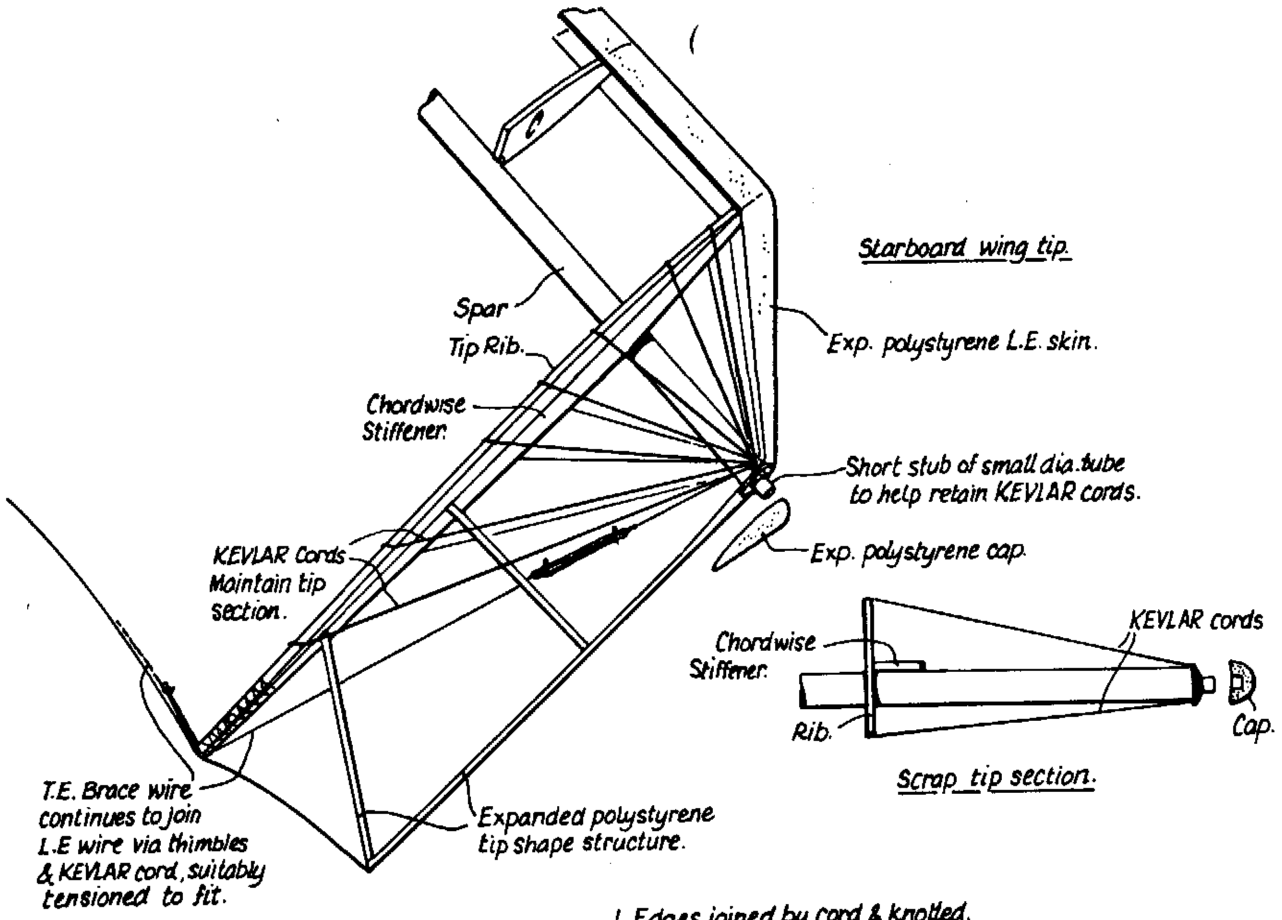




Perspective view of Typical Wing Construction.

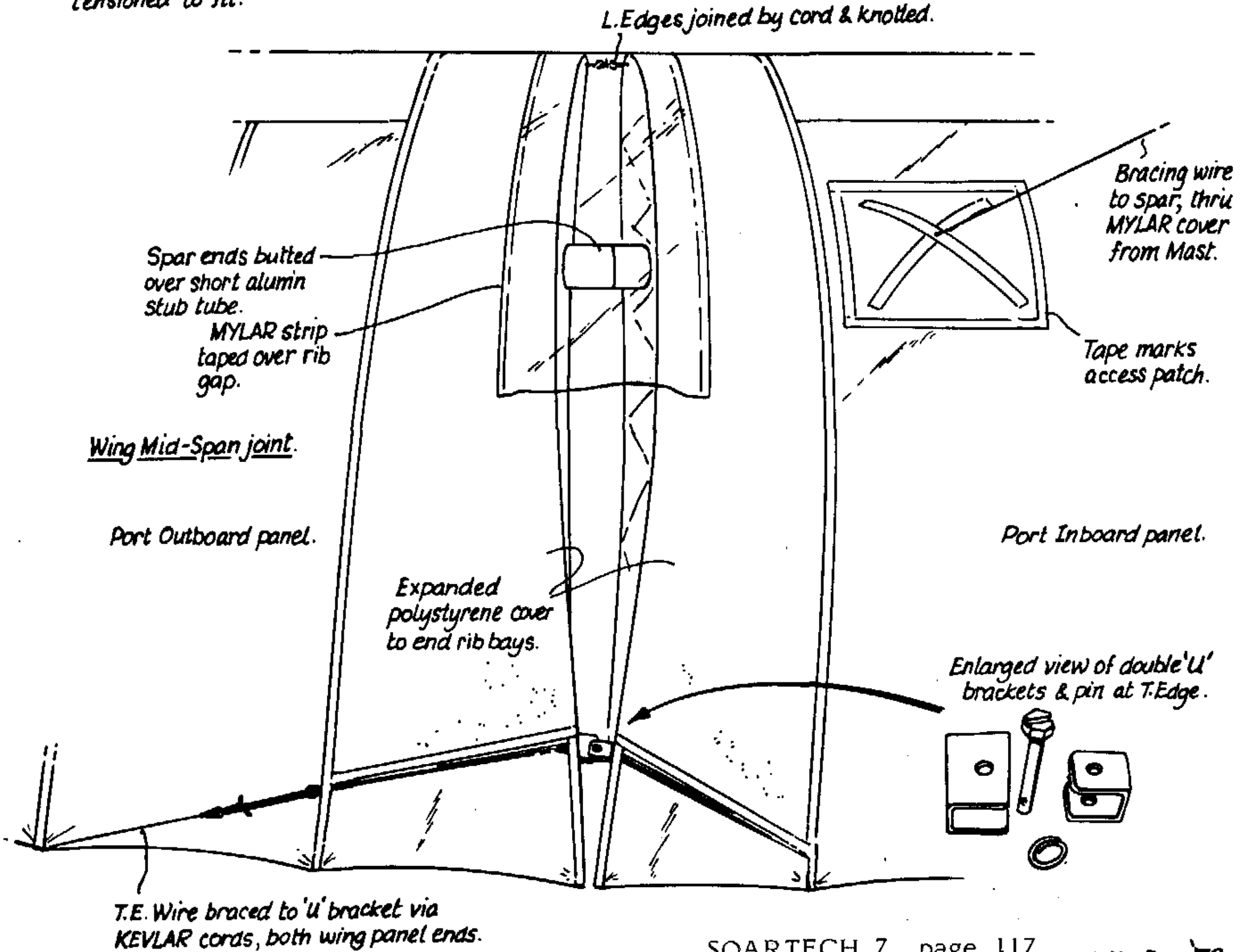
A A P LLOYD '79


Outermost 4" of each blade from Balsa wood Covering 1 layer of "Kevlar" cloth.
2 Spars only at extreme tip.
Spar tube to here
Blade core, Dense Blue foam 2·2lbs Cu/ft. (DOW SM Styrofoam.)
"Spars" made up from 12 lamellae of CF, each ·006", resulting spar is ·095" x ·25 wide. Four spars are inset into foam blade the front pair are the full blade span. The rear two extend out to 26" short of the tip.
Three layers of "Kevlar" scrim cloth are used at the root of each blade, tapered off to 1 layer at the tip. This material is 1·7ozs/sq yd.
4 Spars.
C.F Root tube is 12" long, O/A., 8" fixed in blade root.
Propeller Hub area faired with Exp foam.
'Jubilee' type hose clamp to adjust blade pitch.
A A P LLOYD '79.



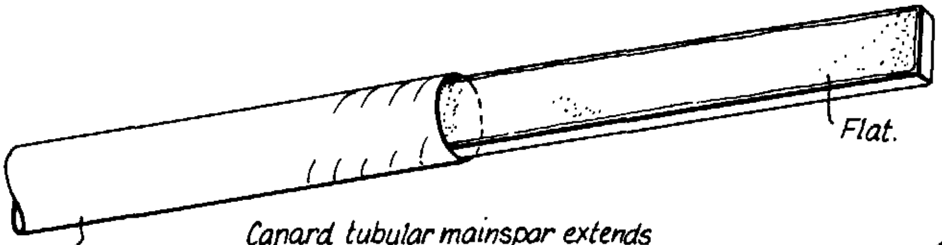
Starboard wing tip.

Scrap tip section.

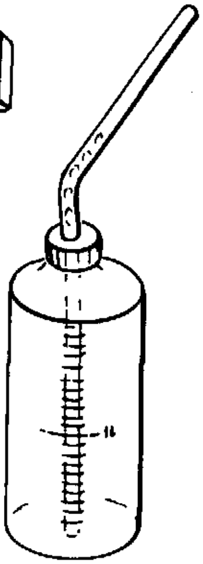


Wing Mid-Span joint.

A.A. Lloyd 79

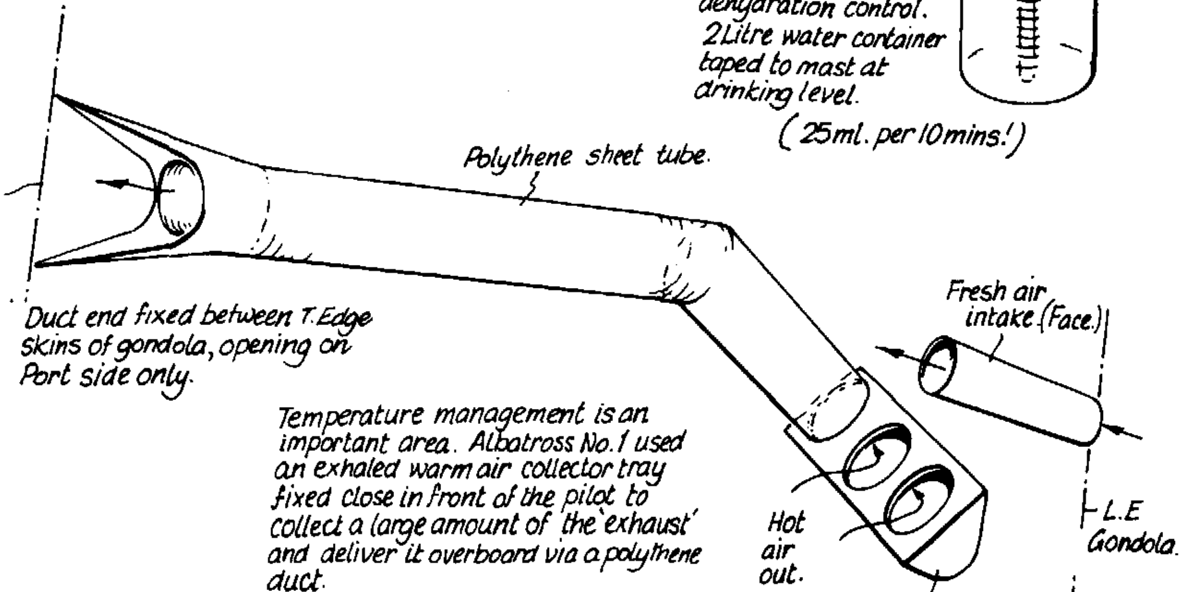


Canard tubular mainspar extends to within 2 rib spaces of each tip. At this point at each tip the spar extension is a flat Expanded polystyrene (Styrofoam) strip re-inforced with CF tape.



Pilot's humidity/ dehydration control. 2 Litre water container taped to mast at drinking level.

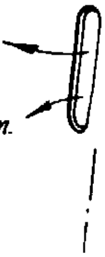
(25ml. per 10 mins.!)



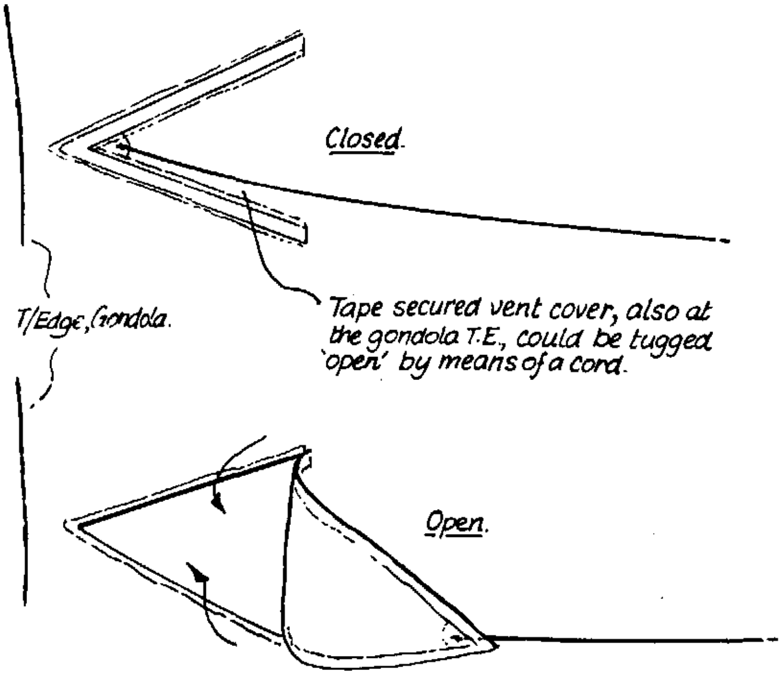
Duct end fixed between T.Edge skins of gondola, opening on Port side only.

Temperature management is an important area. Albatross No.1 used an exhaled warm air collector tray fixed close in front of the pilot to collect a large amount of the 'exhaust' and deliver it overboard via a polythene duct.

Exp. Polystyrene tray.

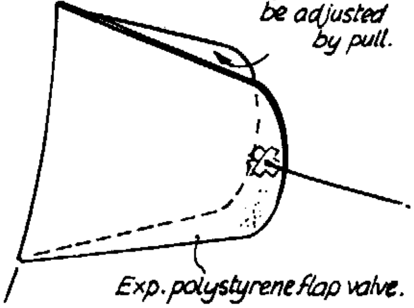


Fresh air inlet at 'Bowsprit' projection. (Waist height.)



Tape secured vent cover, also at the gondola T.E., could be tugged 'open' by means of a cord.

Albatross No1 also had a second vent at the gondola T.E., this one was spring bias closed, and could be adjusted by pull.

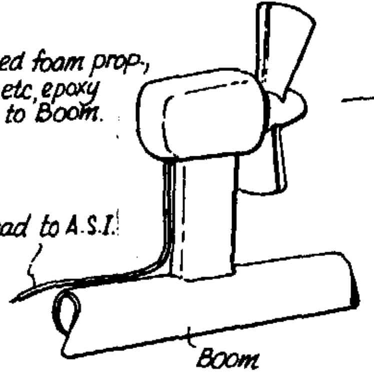


Exp. polystyrene flap valve.

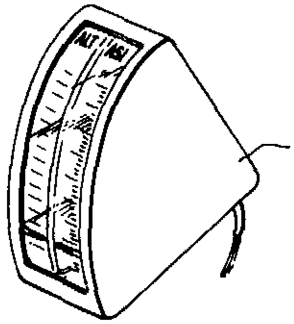
AAPLLOYD—79.

Instrumentation, Radio & Electronics Equipment.

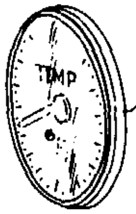
Expanded foam prop., fairings etc, epoxy & taped to Boom.



Propeller, driven by Airflow, in turn drives slotted disc, which interrupts an L.E.D. display to a photocell sensor thus producing countable impulses.

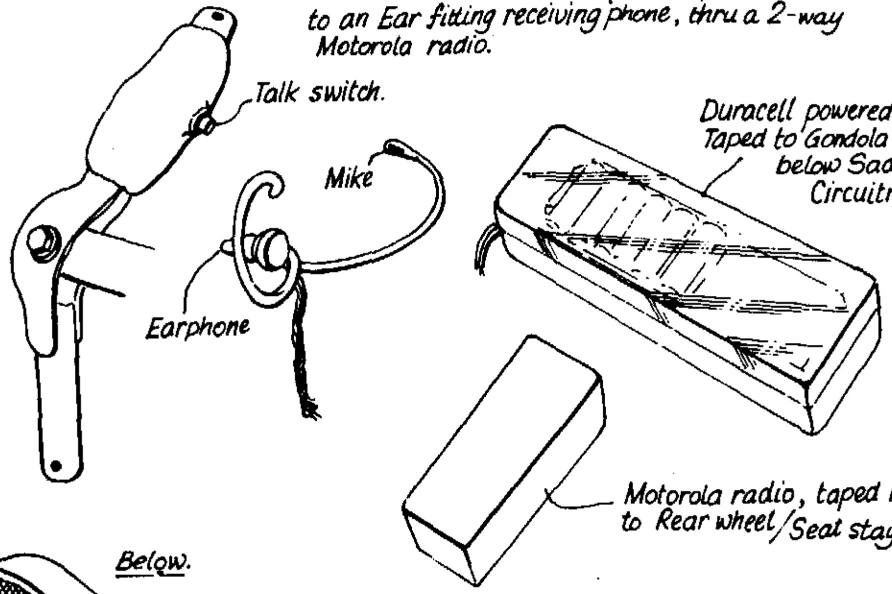


Combined Altimeter & Airspeed Indicator, taped to Mast, port side, at pilot's eye level.



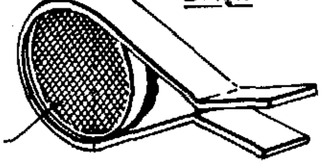
Internal temperature indication of Gondola/cabin via small Bi-metallic type thermometer stuck to panel below window of Gondola.

Radio contact via a Boom Microphone, with a "Talk" switch on Left hand controls, attached to an Ear fitting receiving phone, thru a 2-way Motorola radio.

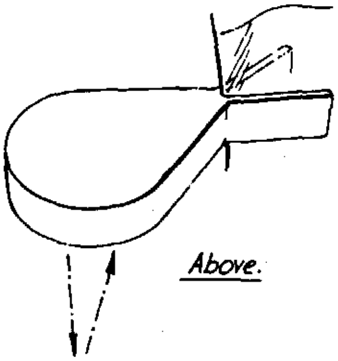


Duracell powered Battery pack Taped to Gondola cross tube below Saddle. Circuitry also contained in here.

Motorola radio, taped in place to Rear wheel/Seat stay tube.



Below.



Above.

Vertical distance measured with this "Sonar" rangefinder cell, from a POLAROID camera. Cell window faces down.

'79.

Gossamer Albatross Propeller

Radius	Chord	B
16.39"	8.62"	56.8°
21.86	9.74	48.5
27.32	9.81	42.3
32.79	9.35	37.5
38.25	8.66	33.8
43.71	7.86	30.8
49.18	7.03	28.3
54.64	6.17	26.3
60.11	5.25	24.7
65.57	4.22	23.2
71.04	2.96	22.0
76.50	0	

Note:

1. Subtract 5.3° from B to get angle between flat bottom of airfoil and the plane of rotation of propeller.

2. Make twisted blade from a series of short foam segments (cut by hot wire between jig ribs, so actual twist is nowhere further than ½° from theoretical).

3. Inner 18" or so has compromised shape (shown on plans and in photos, going from Eppler 193 airfoil to fatter symmetrical airfoil near shaft to accomodate 1" diameter prop spar).

4. 1/4 of chord is ahead of straight spar line, and 3/4 of chord is behind.

5. 100 rpm, 6.5 lbs. thrust, 16 ft./sec. flight speed, 0.22 horsepower delivered to prop, C_L = 0.65 at all stations.