The Formation Flight of Human Powered Aircraft across the English Channel in the Spring

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Presented at the XVI OSTIV Congress, Châteauroux, France (1978).

Notation

AR	Aspect ratio = b^2/S
BHP	Brake-horsepower = 550 ft-lb/sec = 746 watts = 76 kg_f – m/sec
b	Wing Span
c	Average wing chord = $\frac{S}{b}$
C_L	Lift coefficient
C_D	Total drag coefficient
C_{D_π}	Parasite drag coefficient
C_{D_p}	Profile drag coefficient (wing alone)
C_{D_i}	Induced drag coefficient = $Kw\, C_L^2/\pi\, AR$
C_{D_t}	Trim drag coefficient
C_{D_O}	«Zero-lift» drag coefficient
C_d	Airfoil section drag coefficient (2-dimensions)
C_L	Airfoil section lift coefficient (2-dimensions)
	Drag force = $\frac{1}{2}\varrho V^2 C_D S$
g	Wing-tip gap (formation flight)
h	Height of wing mean aerodynamic chord (MAC) above "ground plane"
K_W	Wing "span efficiency factor"
K	"Airplane" or "Oswald" efficiency factor
K	Inviscid flow induced drag factor (see equation 10)
L	Lift force = $\frac{1}{2}\varrho V^2 C_L S$
n	Design ultimate load factor
R_n	Reynolds number = Vc/ν
S	Wing area
T	Thrust force
V	Flight Speed
W	Flight Weight
z	Height
α	Angle of attack
η	Propeller/Transmission efficiency
ϱ	Air mass density
ν	Kinematic viscosity
$(\ )^*$	Indicates an optimum (maximum or minimum value)
$(\ )_\infty$	Indicates flight in free air outside of ground effect and formation
$(\ )_\omega$	Refers to a value for a wing alone
$(\ )_c$	Refers to a value for a canard surface

Introduction

After nearly twenty years of dedicated effort by groups and individuals around the world, the celebrated £ 50 000 Kremer competition for human powered flight was won 23 August 1977 at Shafter, California, by Dr. Paul B. MacCready Jr's "Gossamer Condor". Rather than end an era in the history of low-speed aeronautics, however, MacCready and company's accomplishment now appears to be only a major milestone. A new Kremer prize of £ 100,000 has been offered for the flight of an unassisted human powered aircraft (HPA) across the English Channel. Thus the goal in HPA development has been shifted from a demonstration of fully controlled HPF to sustained distance flight.

The past history of HPF has been very thoroughly documented in various sources (References 1–5), and the design and flight trials of the «Gossdesign and flight trials of the "Gossamer Condor" have been described in detail in References 6–10. The purpose of the present paper is two-fold:

1. To provide a brief analysis and review of the basic HPA design problem with emphasis on the requirements for an airplane capable of flying across the English Channel, solely under human power.
2. To describe the results of a recent analysis of the aerodynamic consequences of flying a pair of HPA type **vehicles in formation, in and out of ground effect.**

As background for the subsequent discussion, Figure 1 shows a planform/size comparison between three existing HPAs and two modern sailplanes. The characteristics of these machines and others referred to in the text are listed in Table 1.

Not shown in Figure 1 is the recently completed Newbury «Manflier» designed by H. C. N. Goodhart. Aside from the "Gossamer Condor" this machine is the only new HPA of major technical significance to appear in the last two years. The Manflier is a two-place machine with span and wing area very similar to the Herts. "Toucan II". Unlike the Toucan, however, the Manflier is a "span-loader" in which the crew is placed in separate pods, displaced thirty-five feet (11.5 m) on each side of the wing center-line. Each pod is fitted with its own propeller; these serving both for thrust production and, by differential thrust, for roll-yaw control. The "Seattle Show II" HPA listed in Table 1 is a design study which will be discussed later.

A Review of HPA Technical Problems

This section provides a brief review of several of the basic technical problems in ultra-low powered aircraft design.

Power Required:

The simplest way to approach the HPA design problem is to consider the relations for power required in steady, level rectilinear flight. Under these conditions:

(1) Weight = W = Lift = L = $\frac{1}{2}\varrho V^2 C_L S$
(2) Thrust = T = Drag = D = $\frac{1}{2}\varrho V^2 C_D S$

and (in the English system of units, with weight in pounds and speed in feet per second):

(3) Brake horsepower required =

$$BHP_{req} \equiv \frac{DV}{550\,\eta}$$

$$= \frac{WV}{550\,\eta(L/D)}$$

$$= (2/\varrho)1/2\ \frac{W}{550\,\eta}\ (W/S)1/2\ \frac{C_D}{C_L 3/2}$$

$$= \frac{WZ}{550\,\eta}$$

The second of equations (3) clearly demonstrates that "minimum" power required demands that the aircraft have a low weight, high propulsive and aerodynamic efficiency (L/D), and flight should be at a low speed. Further, the third of equations (3) shows that, everything else being equal, weight appearing as $W^{3/2}$ is the single dominant variable in the design problem. It must also be clearly recognized that weight, lift, drag and speed are all strongly coupled with each other and with vehicle "size" and "aerodynamic surface quality».

Power Available:
The power available from a human pilot in various degrees of physical fitness for exercise durations up to about one-half hour has been well established by numerous experimenters. In round numbers, a champion athlete can produce between 0.5–0.6 BHP (using leg muscles alone) for periods on the order of ten minutes. An average fit adult is capable of producing about 0.3 BHP for the same period.

Available, rather meager, data indicate that as exercise duration extends to periods of several hours, the power available levels decay slowly until for periods of exercise on the order of two-to-three hours, the champion athlete (not distracted by the simultaneous demands of flying an unconventional aircraft like an HPA) can produce on the order of 0.4 BHP, while an "average" athlete in good physical condition could be expected to comfortably produce 0,3 BHP even while flying. This latter value is used as the nominal long duration cruise condition in the remainder of this paper.

Weight:
The structural design and consequent weight of an ultra-low density HPA is inadequately covered in the aeronautical literature. Three major papers of great interest on this topic exist (References 11–13) however, all of which are devoted to the design requirements of highly efficient (aerodynamically) cantilever winged HPAs. These articles give little guidance for the wire-braced "hang glider" type structure which characterizes the "Gossamer Condor" and one might most profitably consult the model airplane literature on this topic (c.f. Hacklinger, Reference 14).

HPA structures can be basically characterized as large with design load factors only sufficient to provide a necessary strength margin during flight in nearly calm air while the machine is operating close to the ground. The surface quality of the wing structure is strongly dependent on the ingenuity and skill of a designer in meeting the conflicting requirements of extremely low weight while providing sufficiently close rib spacing and sheathing in the region of the wing leading edge to acheive good aerodynamic performance.

As a reference point, a general size/weight relationship for the classic cantilever monoplane HPA configuration which seems to give reasonable estimates has been derived (Reference 15). This formula states (in the English system of units with weights in pounds and span in feet):

$$W = U + C_{\omega} (nU)^{p} (bAR)^{p} \quad (4)$$

$$U = \begin{cases} 200 \text{ lb. single place HPA} \\ 370 \text{ lb. two place HPA} \end{cases}$$

$p = 0.58$

$C_{\omega} = 0.029$

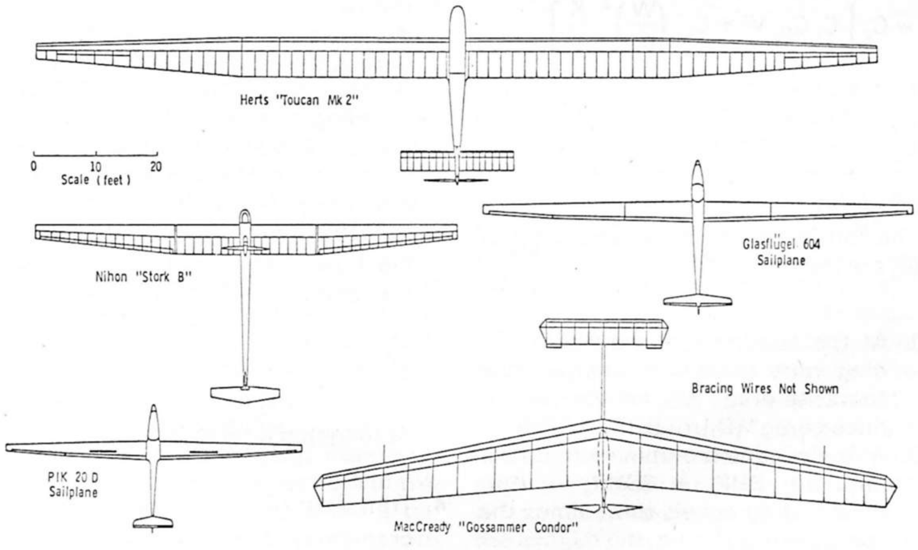


Figure 1 HPA SIZE/PLANFORM COMPARISON

Table 1
Typical Human Powered Aircraft and Sailplane Characteristics

Type	Crew	Wing Span ft (m)	Wing Area ft² (m²)	Aspect Ratio	Weights Empty lb (kg)	Weights Loaded lb (kg)	Wing Loading lb/ft(kg/m²)	Nominal Cruise Speed mph (km/hr)
Nihon U. "Stork B" (Japan)	1	68.8 (21.0)	234 (21.75)	20.3	79 (35.8)	207 (93.9)	0.88 (4.29)	~19 (30.6)
Herts "Toucan MkII" (U.K.)	2	139.0 (42.4)	696 (64.7)	27.8	241 (109)	540 (245)	0.78 (3.8)	~17 (27)
Mac Cready "Gossamer Condor" U. S.)	1	96.0 (29.3)	720* (66.9)	12.8*	70 (31.7)	210 (95.2)	0.29* (1.4)	10–11 (16–18)
Newbury "Manflier" (U.K.)	2	137.8 (42.0)	648.3 (60.3)	29.3	~160 (72.6)	~460 (209)	0.71 (3.5)	~16 (26)
"Seattle Slow II" (U.S.) (Theory)	2	140 (42.7)	1130* (105.0)	17.3*	140 (63.5)	~420 (140)	0.37* (1.8)	11 (18)
PIK 20D (Sailplane)	1	49.2 (15.0)	107.6 (10.0)	22.5	485 (220)	992 (max) (450)	5.9–9.2 (28.8–44.9)	59–73** (95–118)
Glasflügel 604 (Sailplane)	1	72.2 (22.0)	175 (16.3)	29.8	926 (420)	1310 (599)	7.54 (36.8)	61** (98)
Astir CS (Sailplane)	1 1	49.2 (15.0)	136.5 (12.7)	17.7	528 (239)	840 (381)	6.15 (30.0)	51** (82)

*Mainplane only for reference **At L/D maximum

Aerodynamic Performance

The entire topic of the aerodynamic characteristics of an HPA, even in the case of level rectilinear steady flight is complicated by several factors, among which are:

1. The flight speed is unconventionally low, so that even with a very large chord wing, the Reynolds number range is substantially below that of conventional sailplanes. Precious little experimental data on airfoil sections suitable for HPA applications in this Reynolds number range exist.
2. There is a very strong coupling between structural weight limit imposed restraints on achievable surface quality, and thus use of sailplane type airfoils with very long runs of laminar flow are difficult to justify. In this light, pre-WWII sailplanes seem a better aerodynamic model for an HPA than more modern fiberglass machines.
3. The optimum design lift coefficient range (corresponding to flight in the region between maximum lift-drag ratio and minimum power) is generally beyond that of sections designed for normal sailplane operations.

Beginning with the work of Wortmann and Eppler, our understanding of airfoil section design, particularly in the areas of high lift, single element sections at "low" Reynolds numbers has greatly increased in the past twenty years. Recent advances by R. H. Liebeck (Reference 16), M. L. Henderson (Reference 17) and others in the United States demonstrate the possibilities of designing high performance sections suitable for HPA applications with design lift coefficients in the range $1.0 \leqq C_L \leqq 1.6$ over the Reynolds number range $2 \times 10^5 \leqq R_n \leqq 10^6$. Such sections demand only limited runs of laminar flow (depending on the profile drag values desired). The basic HPA airfoil design problem has been well discussed in a recent paper by Dr. Wortmann (Reference 18).

Drag Analysis:

In classical first order aerodynamics, it has been customary to use the parabolic drag approximation in making performance estimates. This formula, which represents nothing more than a curve fit over a portion of the aircraft drag polar, is frequently misunderstood and misused, particularly when estimates of power required or sailplane sink rate in the region between the point of maximum lift-drag ratio and stall are to be made. A further point of confusion among amateur aerodynamicists is the relationship between the formal wing-alone "span efficiency factor" (K_w) and the so-called "airplane" or "Oswald" efficiency factor (K) for a total configuration. (As used here, the factors correspond to the reciprocals of those defined by Oswald and Munk, and thus should strictly be thought of as "span inefficiency factors", Editor). In its usual form the parabolic approximation is:

$$(5)\ C_D = C_{D_o} + \frac{KC_L^2}{\pi AR}$$

Substitution of equations (5) and (1) into equation (3) yields the result:

$$(6)\ BHP_{reg.} = BHP_o + BHP_i$$

$$= C_0 \left[C_1 C_{D_o} V^3 + C_2 \left(\frac{W}{b}\right)^2 \cdot \frac{K}{V} \right]$$

$C_0 = {}^1\!/_{550}\, \eta$
$C_1 = (2W/\rho S)^{1/2}$
$C_2 = {}^2\!/\pi\rho$

The formal results of equations (5) or (6) are that:

1. At the condition of maximum lift-drag ratio (minimum energy), the "parasite drag" (D_o) equals the "induced drag" (D_i), or $BHP_o = BHP_i$.
2. At the condition of minimum power required, $BHP_i = 3BHP_o$ or "induced" drag equals three times the "parasite drag".
3. The optimum lift coefficients for an aircraft of given geometry (shape and AR) are:
   (7) $C_L{}^* = [C_{D_o} \pi AR/K]^{1/2}$ maximum L/D $C_L{}^* = [3 C_{D_o} \pi AR/K]^{1/2}$ minimum power
4. According to equation (6), the "parasite" (zero lift) power required varies as the cube of the flight speed, while the lift dependent "induced" power varies as the inverse of the speed.

The nature of the parabolic drag polar approximation to the actual detailed drag variation with lift coefficient (and Reynolds number) for a modern unflapped fiber glass sailplane (the Eppler/Grob "Astir CS") is shown in Figure 2.

The Astir is used by the Boeing Company for airframe aerodynamic noise research and the drag analysis has been made using measured wing boundary layer data for estimates of section profile drag. The drag polars shown in Figure 2 are for the machine at a fixed weight of 840 pounds (381 kg) reduced to standard sea level conditions. The lift coefficient scale can be converted to a Reynolds number scale (R_n based on a average wing chord) through the relation:

$$(8)\ R_n = ({}^2\!/_{\rho\nu^2})^{1/2}\, (w/c_L AR)^{1/2} = \frac{V\bar{c}}{\nu}$$

The bookkeeping scheme used in the detailed breakdown shown in Figure 2, apportions the drag in the following way:

1. Parasite drag (C_{D_π}) – the parasite and interference drag contributions of all components of the aircraft except the wing.
2. Profile drag (C_D – the profile drag of the wing alone, calculated by integrating the airfoil section drag coefficients (C_d) accross the span accounting for wing planform (i.e. chord) variation; and hence section lift coefficient and Reynolds number change accross the span.
3. Induced drag (C_{D_i}) – the actual inviscid flow drag-due-to-lift term, depending on planform, twist, etc.

   $$(C_{D_i}) = \frac{Kw\, C_L^2}{\pi AR}$$

   Noting that $K_w \neq K$
4. Trim drag (C_{D_t}) – the combined increments of parasite, profile and induced drag generated in holding the aircraft in trim at a given flight attitude.

The purpose in providing this tutorial in drag estimation are to emphasize that a simple parabolic drag polar, while indicative of trends in power required with speed and size variation, is not an adequate substitute for a detailed drag analysis in the region of minimum power required, and to make the following specific points:

1. The differences in numerical values between the parabolic curve fit parameter (K) and the analytically determinate wing span efficiency factor (K_w) are due to Reynolds number variation accompanying the change in lift coefficient and the inclusion of the lift (or angle of attack)

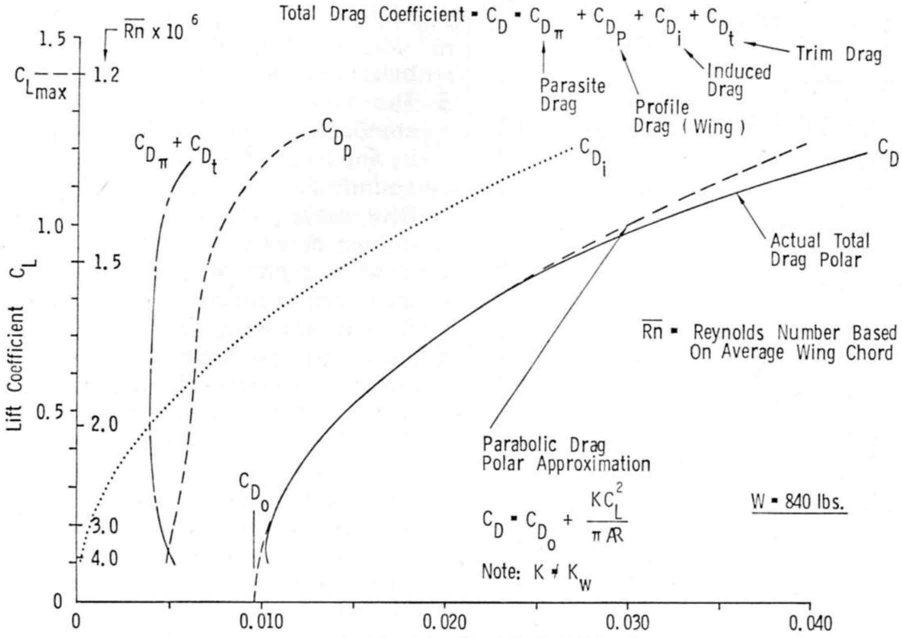


Figure 2 DETAIL DRAG BREAKDOWN FOR THE ASTIR CS SAILPLANE

dependent components of parasite, profile and trim drag into the single lift-dependent term in the parabolic polar approximation.

2. Application of a parabolic polar approximation over a range of lift coefficients beyond which it is valid, leads to inaccurate consequences in either prediction of optimum lift coefficient (e.g. at minimum power) or, at a fixed lift coefficient, of optimum aspect ratio.
3. Many previous studies of HPA design requirements (e.g. Reference 19) are marred by one or both of two factors: (a) blind reliance on the parabolic polar, (b) application of theoretical results on drag reduction in ground effect to the entire parabolic "induced drag" term rather than to the purely inviscid induced drag term in a detailed drag analysis (i.e. confusing the factor K with K_w).

Induced Drag Reduction and Ground Effect

HPA performance is very marginal even in simple rectilinear flight. Near the condition of minimum power, the induced drag is such a major component, that methods of reducing the induced power required have always been sought as a central key to successful HPA operations. In general there are four direct ways to decrease pure induced drag: (1) decrease span loading (w/b) (2) employ a non-planar wing (e.g. winglets) if geometric span is constrained, (3) capitalize on ground effect and (4) place two or more "small" wings in formation.

Outside of ground effect, decreasing the span loading of an optimally loaded planar wing is the most effective means of reducing induced drag. Size and weight limits confine this approach in the HPA case, however. Non-planar wings are a possibly viable approach, particularly if the machine must execute turns. However, in rectilinear flight, the profile drag of the "winglet" surface substantially diminishes the potential reduction in overall drag. In pure rectilinear flight, turning the winglet into pure span increase is a generally superior solution.

The observed reduction in induced drag due to ground effect when operating a wing at moderate height-to-span ratios ($0.05 \leqq h/b \leqq 0.3$) has long been considered a cornerstone in HPA design. The theoretical influence of ground plane proximity on an optimally loaded wing is shown in Figure 3. These results assume that the wake from the wing is planar and that there is no roll-up of the trailing vortex sheet downstream of the wing.

The fourth method of induced drag reduction, not previously proposed for possible application to the HPA cruise problem, involves flying a pair or ensemble of relatively smaller HPA's in formation. This idea is inspired by the example from nature of the long range migrations of birds, which can be considered a direct natural equivalent of the cross-Channel HPA performance problem. The results of an analysis of two optimally loaded wings alone, in and out of ground effect, with various ratios of gap-to-span are shown in Figure 4. The results of this analysis, generated by a Boeing vortex lattice computer program developed by W. Feifel (Reference 20), will be discussed in more detail in a later section of this paper.

The Basic HPA Design Problem

To demonstrate the nature of the basic HPA design problem and its relationship to the equivalent problem of motor glider design, a simple calculation was made of the power requirements of a machine with the aerodynamic characteristics of the "Astir CS" sailplane shown in Figure 2 and Table 1, at motor glider and HPA flying weights. The results of this analysis are shown in Figure 5.

In this example, it was assumed that the dimensions of the machines in both cases were those of the basic Astir, and that the drag characteristics shown in Figure 2 do not change with Reynolds number, from those values already established for the actual sailplane. Thus the aerodynamic characteristics of the machine in its low weight (W = 205 pounds) HPA configuration is very substantially optimistic. It is further assumed in the motor glider case that the power plant installation is dragless and engine weight is included in the 840 pound (381 kg) weight. In both cases, propeller effi-

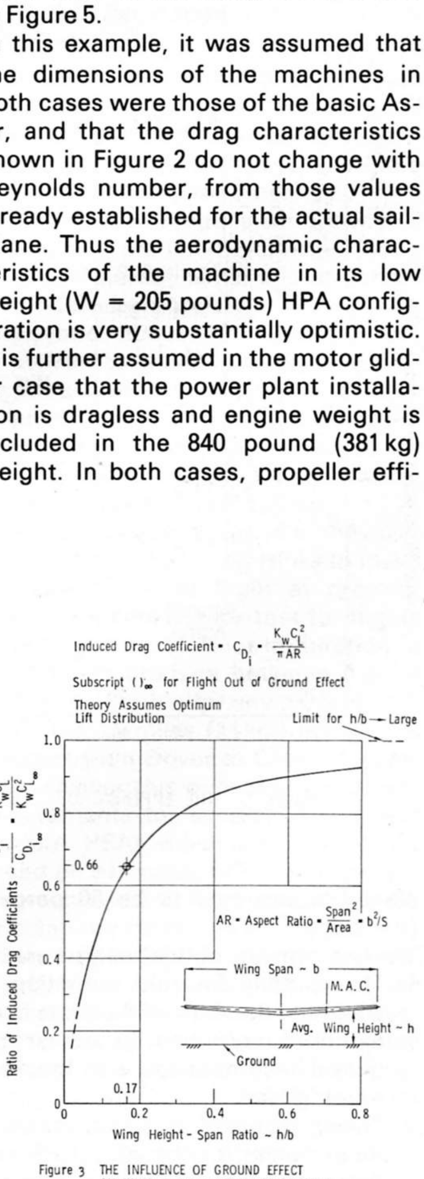


Figure 3 THE INFLUENCE OF GROUND EFFECT ON WING INDUCED DRAG COEFFICIENT

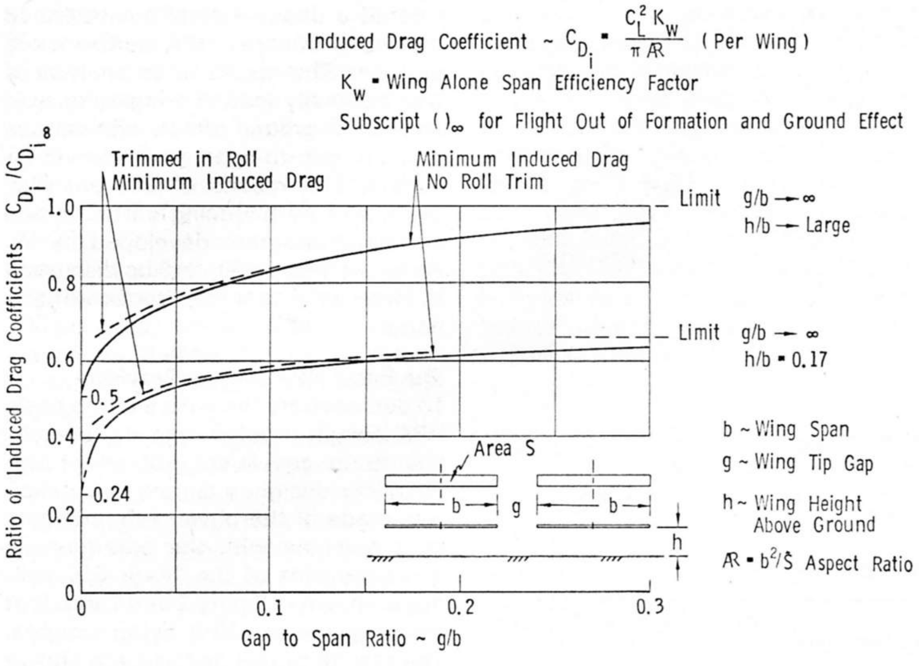


Figure 4 INFLUENCE OF FORMATION FLIGHT ON WING ALONE INDUCED DRAG COEFFICIENT

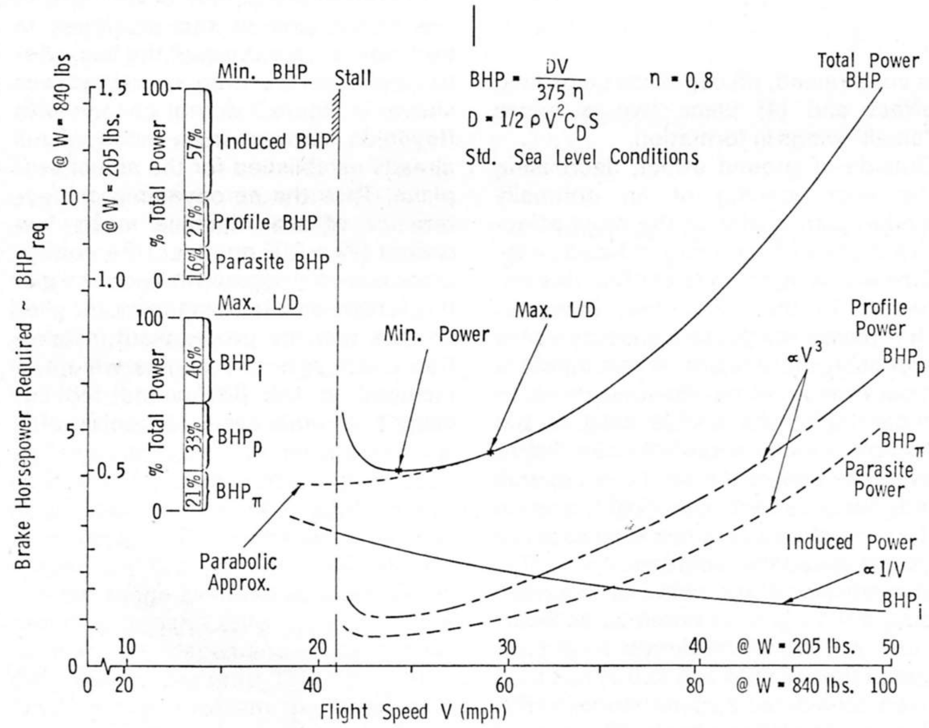


Figure 5 THE EPPLER/GROB "ASTIR CS" SAILPLANE AS A MOTOR GLIDER

ciency is assumed to be 80 percent (η = 0.8).

The basic results of this analysis are:

1. The roughly fourfold reduction in weight of the Astir HPA results in an eightfold reduction in power required in comparison with the Astir motor glider.
2. The corresponding speeds for minimum power for the Astir HPA and Astir motor glider are 23 mph (37 kph) and 48 mph (77 kph) respectively; a reduction by a factor of about two for the HPA.
3. At the condition of maximum lift-drag ratio, the actual inviscid induced power is 46 percent of the total, against a value of 50 percent according to a parabolic approximation to the drag polar.
4. At the point of minimum power required, the actual induced power is 57 percent of the total against the "75 percent" predicted by the parabolic polar value.
5. The minimum power required (at standard sea level) for an Astir quality and sized HPA weighing only 205 pounds out of ground effect is 0.5 BHP, making it barely feasible as a human powered airplane when piloted by a champion athlete under ideal meteorological conditions (zero wind and turbulence).
6. Assuming the Astir HPA flies at a height such that the wing mean aerodynamic chord (M.A.C.) is five feet above the ground (h/b = 0.1), the actual induced drag would be reduced (according to Figure 3) by about 50 percent, resulting in a minimum power required of 0.36 BHP; a 28 percent reduction over the out-of-ground effect value.

In practice, it is virtually impossible to construct an HPA with sailplane quality aerodynamic surfaces within the required weight limits, and the necessarily low flight speed usually results in a substantial Reynolds number reduction compared to that of a normal sailplane. As a general rule, in the range of Reynolds numbers within which an HPA can operate, drag varies with Reynolds number to a power between –0.5 and –0.2, and maximum lift coefficient varies approximately as the 0.1 power of R_n. Thus the designer following a conventional cantilever monoplane approach to the HPA problem is forced into a rather narrow box where weight varies approximately according to equation (4), wing area varies with the inverse square of the flight speed (at a given C_L value) and parasite (and profile) and induced drag vary as the cube and the inverse of the speed respectively. The usual result is a machine with a cruise speed in the range between 15 and 20 mph (24–32 kph) varying in size and weight between the limits established by "Stork" and "Toucan".

It must be noted that all this discussion considers a conventional HPA in purely rectilinear flight. A whole range of additional problems arise when one considers the design requirements of an HPA which must perform the turns required by the rules for the original Kremer competition with its Figure 8 course. None of the classic "high speed", high aerodynamic efficiency HPAs has ever succeeded in making the required turns on a reliable basis. One can state in retrospect that the problem of unlimited rectilinear human powered flight has been solved in principle ever since the famous flight trials of John Potter in the "Jupiter" in 1972 (Reference 1 and 2). The turns however, represented a virtual stone wall until the advent of MacCready's "Gossamer Condor".

A further major practical difficulty arises in classic cantilever monoplane approach to highly aerodynamic efficient HPF. The wings must be very carefully constructed for both light weight and true contours. Thus they become extremely time consuming to construct, time consuming to repair in the event of an accident, and very difficult to modify if design mistakes are discovered. All of these factors help to explain why progress towards the goal of fully controlled HPF has been painfully slow.

MacCready's Gossamer Condor

The modern era of HPF traces its origins to the latter 1950's and until the early 1970's the three almost universal design motivations were: the aerodynamics of the modern sailplane, the structural techniques of the free-flight model airplane, and a fear of the wind. This last factor drove designers towards the high end of the feasible speed range, and the aerodynamic and structural techniques followed as a natural consequence as attempts were made to keep aircraft size within some reasonable bounds.

However, if the wind is not allowed to override other considerations, an alternative approach to the design problem is suggested by equations (3) and (6). If weight is reduced sufficiently in a machine of sufficient size, a major reduction in aerodynamic efficiency (L/D) may be acceptable. This introduces the possibility of employing the elementary rigid wing hang glider or the indoor model airplane as alternatives to the sailplane paradigm for HPA development. One need only reduce the speed of a wire braced (and consequently very low weight) machine and because of the cubic-with-speed variation, the parasite drag is acceptable, and a technically viable solution to the problem results.

A fundamental side benefit to this approach is that the wing becomes relatively simple to build, quick to repair and "easy" to modify. These realizations came to Dr. MacCready and the result has been the triumph, aided by substantial good fortune, of the Gossamer Condor.

With access to a very large and level airfield with favorable weather conditions, a sufficiently large hangar for fabrication and fully rigged storage, and the time and dedication of a group of skilled craftsmen and engineers, MacCready was able to solve the formidable HPA control and turn problems by theoretically enlightened cut-and-try. From the vantage of the earlier viscisitudes suffered by HPF pioneers with machines like SUMPAC, "Mayfly", "Puffin" and "Toucan", the site at Shafter, California, plus MacCready's resources must be viewed with substantial envy. These factors do not seriously detract from the brilliance of the MacCready team's solution to the Kremer Competition design problem. However, it must also be observed that the "Gossamer Condor" did not arise full blown from a vacuum. MacCready's team owes much to the hardwon lessons learned by its predecessors.

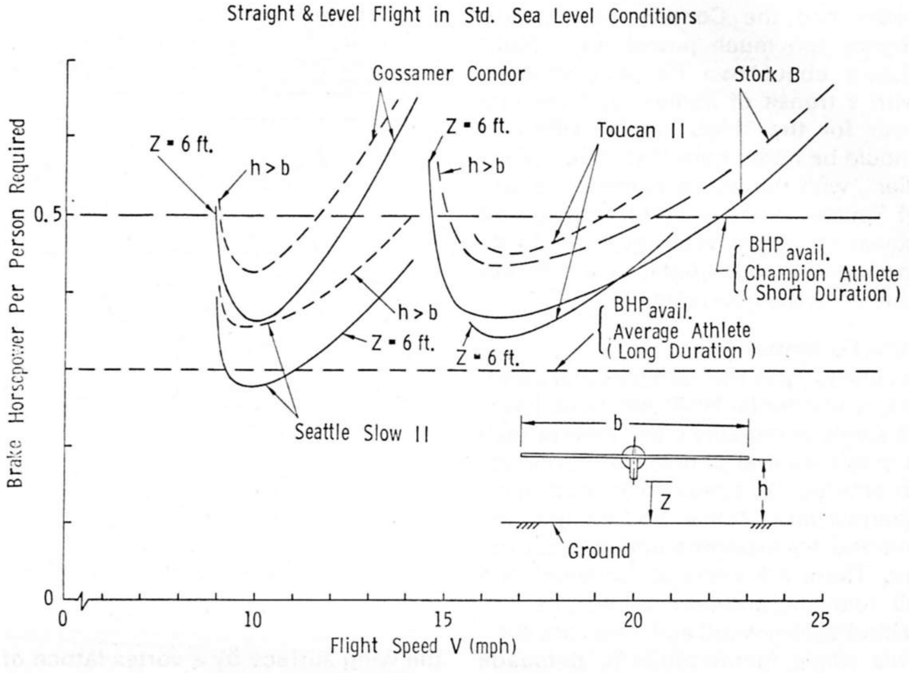


Figure 6 POWER CURVES FOR SEVERAL RECENT HPA's

Across The English Channel

Aside from the fact any human carrying aircraft that can cruise on less than one-half horsepower per crew member represents a fascinating technical challenge, the task set for the new Kremer competition is more challenging operationally than aerodynamically. The major new aspect in the purely technical problem is that a designer can now, with some confidence, consider a wider range of configurations, sizes and design speeds than was thought feasible a decade ago. It is now possible to consider seriously designs ranging in wing span from 70–150 feet (21–46 m) flying at speeds between 8 and 20 mph (13–32 kph) with flying weights between 200 and 250 pounds (90–115 kg) per crew member.

Within this range of values, there are two distinct design approaches:

1. If the speed range is set between 8 and 12 mph, (13–19 kph) the "hang glider" aerodynamic and structural model is appropriate.
2. Beyond about 12 mph, the pre WWII "sailplane" model is appropriate and then one tends to favor an HPA with a "high" cruise speed (16–18 mph) since it maximizes the difference between reasonable wind speed and flight speed.

The question now arises as to the ability of any of the existing HPAs to make the cross-Channel flight at present. That is, if one assumes that for flights of greater than an hour in duration, a human can produce between 0.3–0.4 BHP, is it possible for any current HPA to fly the 21 miles (34 km) across the Channel from Dover to Calais. To partially answer this question, the power requirements for several of the best modern HPAs have been calculated based on estimates of drag in and out of ground effect. The results of these calculations are shown in Figure 6.

The curves in Figure 6 indicate that depending on ones estimate of power available for long duration exercise, Stork, Toucan and Condor are all very marginal candidates as they exist now, even with possible optimistic benefits in power reduction through groud effect. In our view, the Stork is marginally too small, the Toucan II is a bit too heavy and the Condor may require slightly too much power for a flight lasting about two hours, compared with a transit of something over one hour for the "high speed" HPAs. It should be noted here that if the "Manflier", with the aerodynamics and size of Toucan II and a better anticipated power-to-weight ratio, lives up to its expectations, it should have a first rate change at the new prize.

HPA Formation Flight

As one juggles the variables and ponders fundamental HPA questions (such as single or multiple crew, slow or fast) a single central conclusion continues to emerge. At some point theoretical analysis must cease, and enlightened cut-and-try experimentation must begin. There are limits to "science" and all relevent answers cannot be obtained before wood and metal are cut.

This single factor tends to persuade the present authors that the relative "simplicity" of the Gossamer Condor is the single true mark of genius in its concept. The question then arises as to what possibility exists for extending this concept of simplicity of construction and modification to an extremely low-powered HPA capable of flights of over twenty miles or several hours duration, piloted by other than an superman.

In view of the fact that the existing Gossamer Condor works very well indeed, and that a power reduction on the order of 15–20 percent over that of the present machine should bring flights of very long duration within reach of "average" athletes (in favorable weather) a simple method for accomplishing such a reduction has been sought. Thus arose the possibility of a formation flight by a pair of existing Condors. The formation idea sprang in part from an analysis performed by Dr. P. B. S. Lissaman (chief aerodynamicist on the Condor project) and C. A. Shollenberger (Reference 21), although the basic phenomenon has been well understood for decades. The initial analysis of the problem reported here was restricted to a pair of wings alone and resulted in the curves shown previously in Figure 4.

Subsequently, Feifel's vortex lattice wing analysis and design program was applied to a "full configuration" analysis of optimized formation flight. The specific geometry analyzed is shown in Figure 7, and is basically that of the existing Gossamer Condor somewhat simplified. The results shown earlier in Figure 4 are based on a replacement of the wing surface by a vortex lattice of 40 equally spaced panels spanwise and six chordwise panels on each surface. The full configuration analysis uses 40 panels spanwise and only a single bound vortex (lifting line) on each main wing panel in the interest of economy. The vertical "pod" is modelled with a single bound vortex and four panels lengthwise.

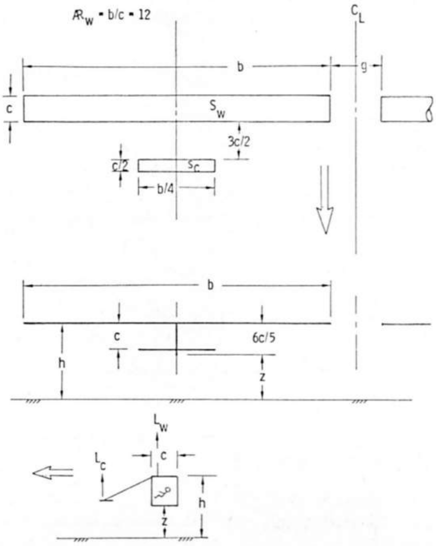


Figure 7 FULL CONFIGURATION HPA GEOMETRY MODEL

For the examples analyzed, the wing and canard surfaces were both specified to carry a nominal lift coefficient of unity (based on their individual areas). Thus the total lift coefficient (C_L) for the configuration, using wing alone area for reference is:

$$(9)\ \bar{C}_L = \frac{C_{L_w} S_w + C_{L_c} S_c}{S_w}$$

$$= \frac{W}{\frac{1}{2}\rho v^2 S} \qquad C_{L_w} = C_{L_c} = 1.0$$

In the analysis, the program computes the near field lift, and the optimum induced drag coefficient (C_{D_i}) calculated in the Treffetz plane (i.e. far down stream of the wing). For a given planform, the required twist distribution for optimum loading at the design condition is determined. The inviscid induced drag factor ($\bar{K}$) for the configuration is defined here as:

$$(10)\ \bar{K} = \bar{C}_{D_i} \pi AR/\bar{C}_L{}^2$$

where $\bar{C}_{D_i}$ uses S_w as a reference.

The results of the formation flight induced drag analysis for whole configurations is shown in Figure 8 for the following four cases:

I. $h/b \to \infty$ – Not trimmed in roll.
– Trimmed in roll aerodynamically.

II. $h/b = 0.17$ – Not trimmed in roll.
– Trimmed in roll aerodynamically.

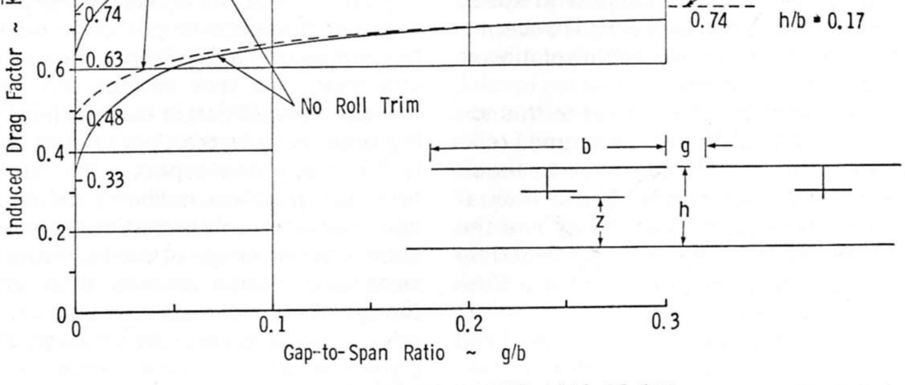


Figure 8 INFLUENCE OF FORMATION FLIGHT ON INDUCED DRAG OF FULL CONFIGURATION HPA

Some example optimum span loadings for the wing are shown in Figure 9. Figure 8 shows that it is preferable to trim the two components of the formation in roll by offsetting the center-of-gravity of each (i.e., nonsymmetric lateral location of the pilot pods) rather than accomplish trim by twisting the wing. The second factor shown by both Figure 4 and 8 is that there is little induced drag reduction for a two plane formation unless the gap-to-span ratio is very small (g/b $\leq$ 0.05), and the benefit of the formation deteriorates when superimposed on ground effect. Figure 9 indicates the penalty of a rather large, heavily loaded canard surface.

Thus, the goal of "simply" producing an HPA with the aerodynamic equivalent of 200 feet (61 m) span, weighing 140 pounds (635 kg) empty, and requiring less than 0.3 BHP/person remains somewhat elusive. Using the induced drag values, slightly modified to account for the sweepback of the Condor wing, it has been calculated that flying two Condors with a gap of only five feet (1.5 m) between the wing tips, results in an 11 percent reduction in power required per person compared with a single standard Condor alone.

Further examination of the results shown in figure 8 indicates that there is little substitute for a large span unbroken (zero gap) wing optimally loaded in reducing induced drag. On the other hand, the structural problems of building a wing like that of the "Manflier" capable of withstanding both normal bending and torsional loads, particularly during ground handling, appear somewhat awesome. Thus, the idea for the present configuration for "Seattle Slow" evolved. "Seattle Slow II", shown in Figure 10, is a conceptual design for a Condor category HPA being considered by a group of Boeing engineers on a avocational basis. No hardware for this machine yet exists. Based on analyses conducted so far, it appears that a pair of "small" Condor type HPA, wire braced and flexibly coupled at the plane of symmetry (so that no bending or torsional moment is carried by the spar at the plane of symmetry) could result in a machine of no more than Toucan II wing span. The machine is designed to fly at eleven mph (18 kph) on 0.3 BHP/person in ground effect. The power required curves are shown in Figure 6 in comparison with those for the Gossamer Condor. It may be noted that the calculated power required by Seattle Slow out of ground effect is about the same as the single Gossamer Condor at a height (measured to the bottom of the aircraft) of six feet (1.8 m) above the ground.

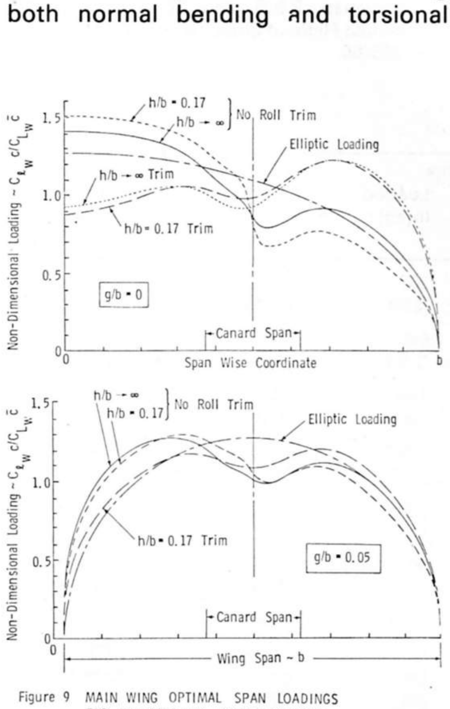


Figure 9 MAIN WING OPTIMAL SPAN LOADINGS FOR COMPLETE HPA CONFIGURATIONS

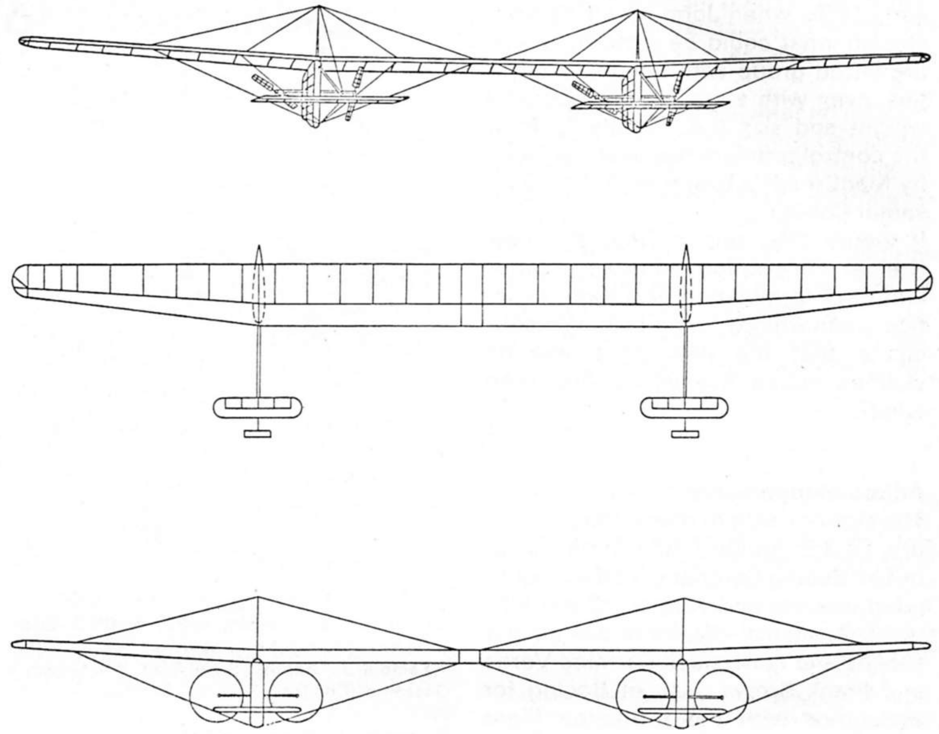


Figure 10 CONFIGURATION OF THE "SEATTLE SLOW II" HPA

Concluding Comments

The goals of this paper have been:

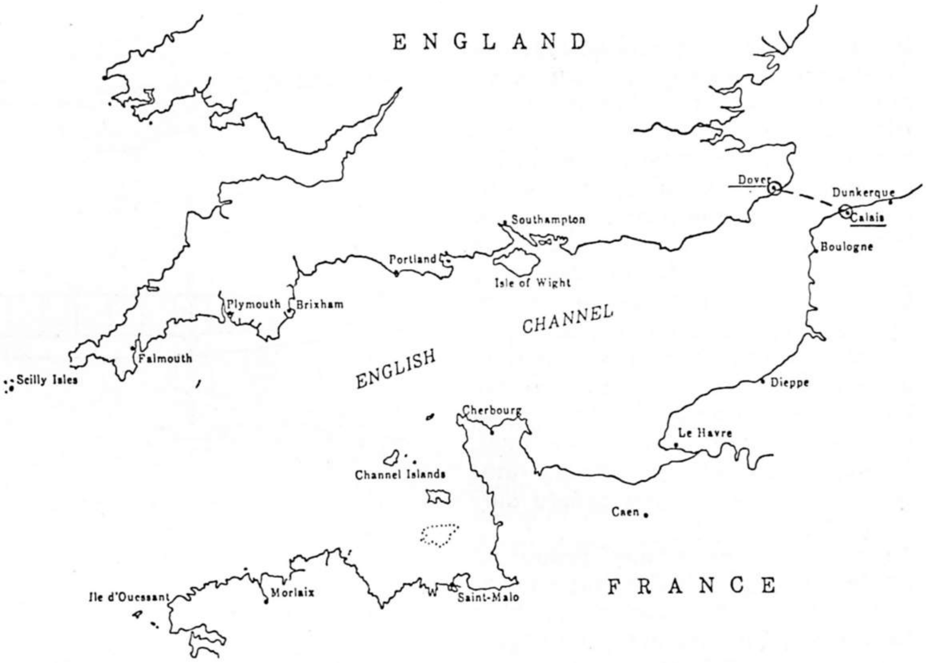
1. To present a current assessment of human powered aircraft design, with emphasis on machines capable of competing for the recently announced £100,000 prize for a flight across the English Channel.
2. To present the results of some recent general analysis on the consequences of flying a pair of HPA type machines in close formation as a possible simple means of reducing induced drag and consequently, power required in rectlinear cruise.

In presenting material on the above topics it has been considered desirable to discuss a number of topics of a fundamental nature (e.g. drag analysis), and thus the paper becomes partially tutorial. We regret any inconvenience to more technically sophisticated readers.

Philosophically, we can find little obvious "practical" merit in HPF. However, on a purely subjective basis, the problem of HPA design remains, to us, enthralling. It must be obvious that HPF represents one near absolute boundary of the feasible human flight spectrum, and the solution of the basic very difficult design and operational problems in HPF must ultimately enlighten attempts to design any practical low-speed flying machine (e.g. motor gliders, ultra-light sailplanes).

On the matter of the Kremer Cross-Channel competition attempted to show that, in principle, the basic technical problem of rectilinear HPF has been largely solved, at least since the early 1970s when John Potter demonstrated what could be done by a well organized group with adequate facilities, even with a machine of marginal weight and size (i.e. "Jupiter"). Now the control problem has been "solved" by MacCready's group with the "Gossamer Condor".

It would thus appear that the new Kremer competition reduces to a problem of determination, fortitude, logistics, meteorology - and luck. We anticipate that the new prize will be claimed within five years. And then what?



Acknowledgements

The authors wish to thank Jerry L. Lundry, Paul E. Rubbert, and Bertil Dillner of The Boeing Company for their continued interest and support of our HPF work. A special thanks is due to our friends and colleagues Carmine Verna and Frank Brown, also of Boeing for assistance with the formation flight analysis and for information provided for this paper.

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Supplement Typical Human Powered Aircraft and Sailplane Characteristics

Type	Crew	Wing Span ft(m)	Wing Area ft²(m²)	Aspect Ratio	Weights Empty lb(kg)	Weights Loaded lb(kg)	Wing Loading lb/ft² (kg/m²)	Nominal Cruise Speed mph (km/hr)
Nihon U. "Stork B" (Japan)	1	68.8 (21.0)	234 (21.75)	20.3	79 (35.8)	207 (93.9)	0.88 (4.29)	~ 19 (30.6)
Herts "Toucan MkII" (U.K.)	2	139.0 (42.4)	696 (64.7)	27.8	241 (109)	540 (245)	0.78 (3.8)	~17 (27)
Mac Cready "Gossamer Condor" (U.S.)	1	96.0 (29.3)	720* (66.9)	12.8*	70 (31.7)	210 (95.2)	0.29* (1.4)	10–11 (16–18)
Newbury "Manflier" (U.K.)	2	137.8 (42.0)	648.3 (60.3)	29.3	~160 (72.6)	~460 (209)	0.71 (3.5)	~16 (26)
"Seattle Slow II" (U.S.) (Theory)	2	140 (42.7)	1130* (105.0)	17.3*	140 (63.5)	~420 (140)	0.37* (1.8)	11 (18)
PIK 20D (Sailplane)	1	49.2 (15.0)	107.6 (10.0)	22.5	485 (220)	992 (max) (450)	5.9–9.2 (28.8–44.9)	59–73** (95–118)
Glasflügel 604 (Sailplane)	1	72.2 (22.0)	175 (16.3)	29.8	926 (420)	1310 (599)	7.54 (36.8)	61** (98)
Astir CS (Sailplane)	1	49.2 (15.0)	136.5 (12.7)	17.7	528 (239)	840 (381)	6.15 (30.0)	51** (82)

*Mainplane only for reference