THE PROSPECTS FOR MAN-POWERED FLIGHT
(THE FUTURE OF AN ILLUSION)

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NOTATION

AR	Geometric Aspect Ratio = b^2/S
AR_e	Effective Aspect Ratio = AR/k
b	Wing Span, ft (m.)
BHP	Brake Horsepower; defined at the interface between the man and the machine. 1 BHP = 550 ft-lb/sec (76 kg-m./sec)
C_D	Total Drag Coefficient
C_{D_p}	Parasite Drag Coefficient (a function of Reynolds number and angle of attack)
C_{D_i}	Induced Drag Coefficient = $k_w C_L^2/\pi AR$
$C_{D_{trim}}$	Trim Drag Coefficient
C_{D_o}	"Zero Lift" Drag Coefficient
C_L	Lift Coefficient
D	Drag Force lb (kg) $D = \frac{1}{2}\rho V^2 C_D S$
k	"Oswald" or "Airplane" Efficiency Factor
k_w	Span Efficiency Factor (Wing Alone)
h	Height of Aerodynamic Center (a.c.) of the Mean Aerodynamic Chord (M.A.C.) of the Wing Above the Ground. ft (m.)
L	Lift Force, lb (kg) $L = \frac{1}{2}\rho V^2 C_L S$
P	Specific Power THP/W
N	Number of Crew Members
R	Turn Radius, ft (m.)
S	Wing Area ft^2 (m^2)
THP	Thrust Horsepower THP = ηBHP
V	Velocity ft/sec (m./sec)
W	Gross Weight, lb (kg)
η	Combined Propeller/Transmission Efficiency $\eta = \eta_p \cdot \eta_t$
ρ	Sea Level Air Density 0.002378 slugs/ft^3 (0.125 kg$_m$/m^3)
φ	Bank Angle deg.
a.c.	Aerodynamic center
M.A.C.	Mean aerodynamic chord

INTRODUCTION

There has been considerable interest and work done during the past decade in attempts to achieve true man-powered flight. Aside from efforts mainly in Germany in the 1930's, the problem had remained dormant for nearly twenty years. In the late 1950's, several individuals in Britain began to reconsider the problem in the light of the great advances made in aerodynamics, materials, and structural technology during the intervening period. Sufficient interest in man-powered flight was stimulated to encourage the British industrialist Henry Kremer to establish the £5000 Kremer Competition in early 1960. The basic rules for this competition require that the "aircraft" take-off and fly a figure-eight course around two pylons placed one-half mile apart on a level field solely by human muscle power. The rules further stipulate that the starting line (which is also to be the finish line) be crossed at a minimum altitude of 10 ft (3 m.); no stored energy devices or lighter-than-air gases are permitted, and the aircraft must be controlled by the crew for the duration of the flight. No limit is set on the number of crew members. The competition was originally open only to citizens of the British Commonwealth.

An excellent historical survey of serious past attempts to achieve man-powered flight, and the status of projects intended to compete for the Kremer prize, up to February 1966 is contained in Shenstone's paper (1). Two significant events which have sustained interest in man-powered flight since the publication of Shenstone's paper have been the change in the Kremer Competition rules in 1967 to allow participation by individuals of any nationality and the doubling of the prize for the negotiation of the basic course to £10,000 (about $24,000 U.S. funds). The current prize is to remain in effect until 31 December 1973; at which time, if the prize has not been won, the Royal Aeronautical Society will consider revision of the rules and extension of the competition.

Since the establishment of the Kremer prize, at least twenty-five serious design studies of "conventional" aircraft capable of competing for the Kremer prize have been undertaken. Of these designs, about a dozen have been built and at least seven have successfully flown following unaided man-powered takeoffs. Five other machines have reached an advanced stage of construction. Table 1 lists the physical characteristics of some of these machines.

In addition, several ornithopters and helicopters have been constructed. It appears, however, that man-powered helicopters have little chance at present to fly far enough out of ground effect to successfully compete for the Kremer prize. While showing some promise aerodynamically, ornithopters must necessarily be rather complex mechanically; and, considering the present state of materials and structural technology, they must be considered a very marginal prospect at best. At least in the near future, one is probably best off concentrating on a more-or-less conventional aircraft layout to solve the problem.

Despite all the recent activity in the field, much of it by teams of very competent engineers, the Kremer prize appears to be a long way from being won. As a consequence, we consider it appropriate at this point in time to critically examine existing designs and perhaps indicate some ways to circumvent shortcomings in current approaches to the problem.

THEORETICAL CONSIDERATIONS

Power Available

The logical place to begin a discussion of man-powered flight is to consider the power available from a man and how this power can be most efficiently extracted. Fortunately, a considerable amount of experimental work has been done on this subject, much of it directly related to the problem of man-powered flight.

Very extensive experiments were conducted at Ursinus' Muskelflug-Institute at Frankfort, largely by Gropp, during the mid 1930s. Gropp investigated factors such as physical condition and training, power-to-weight ratio, and methods of power extraction. While impressive, the work is of somewhat limited value in that it considers only the first two minutes of exercise, and the subjects were mainly Northern Europeans; no information on possible variations due to ethnic factors was given. Gropp's conclusions were that pedaling was probably the most efficient means of power extraction and that a subject in average physical condition was capable of producing on the order of 0.4 BHP after about two minutes' exertion.

Later analyses by Nonweiler (2, 3) and Wilkie (4) extended the time span to several hours. Wilkie concluded that for champion athletes, the steady state work output for exercise durations from 5 to 150 minutes was 0.4 to 0.5 BHP, limited primarily by the ability of the body to absorb and transport oxygen. In addition, for short periods (0.1 to 5 minutes) up to 2 BHP could be produced, for a total of 0.6 HP-minutes, by hydrolysis of chemical substances stored in the muscles. This process would, however, entail going into "oxygen debt." An ordinary healthy individual should be able to produce 70 to 80 percent of these values according to Wilkie. The results of the Ursinus-Gropp experiments and Wilkie's analysis are shown in Fig. 1.

The power levels given in Fig. 1 (assuming pedaling as the best method of power extraction) are more-or-less generally accepted and have been experimentally verified by several groups who have built or are building man-powered aircraft. Two questions remain largely unanswered, despite this body of experimental data: (1) is a man capable of developing his full power potential while suspended several feet above the ground in a flimsy, flexible aircraft? (2) More importantly, what level of power degradation does the pilot suffer while attempting the very difficult task of controlling the aircraft, specifically, around the Kremer Competition course? A further practical difficulty arises in trying to find a first-rate pilot who also happens to be a champion athlete.

On the basis of the above discussion, we propose the following set of possible power equations, assuming:

(1) The pilot is in average physical condition and for purposes of attempting the Kremer Competition, will participate in some sort of physical training program. Thus the steady state power output for periods of 5 to 10 minutes is assumed to be 0.4 BHP, degraded to various assumed levels by the need to concentrate on flying the aircraft.

(2) If a crew of more than one is to be carried, champion athletic performance can be produced by the "slaves." Thus an output of 0.5 BHP per man for periods of 5 to 10 minutes may be expected if additional crew members need not concentrate on flying.

$$\text{BHP available} = 0.40 + 0.50\,(N-1) \qquad 1.1$$

This assumes no degradation in pilot performance with exercise.

$$\text{BHP available} = 0.30 + 0.50\,(N-1) \qquad 1.2$$

This assumes 25% degradation in pilot performance with exercise.

$$\text{BHP available} = 0.35 + 0.50\,(N-1) \qquad 1.3$$

A compromise between the assumptions of 1.1 and 1.2

Power Required

For steady level flight, the power required can be expressed by the formula:

$$THP_{REQ.} = \eta\, BHP_{REQ.} = \frac{W \cdot V}{550\, L/D} \qquad (2)$$

An alternative representation is possible if one eliminates the velocity by use of the definition of the lift coefficient, and the fact that in level flight the lift approximately equals the weight. In this form:

$$THP_{REQ.} = \left[\frac{2}{\rho}\right]^{1/2} \cdot \frac{W}{550} \cdot \left[\frac{W}{S}\right]^{1/2} \cdot \frac{C_D}{C_L^{3/2}} \qquad (3)$$

For purposes of the present analysis, it has been assumed that the drag polar for the aircraft can be approximated with sufficient accuracy over a limited range of lift coefficients and Reynolds number by the parabolic relation:

$$C_D = C_{D_P} + C_{D_i} + C_{D_{TRIM}} \qquad (4)$$

$$\cong C_{D_0} + \frac{K\, C_L^2}{\pi AR}$$

TABLE 1. CHARACTERISTICS OF SELECTED MAN-POWERED AIRCRAFT

Type, Country, First Flight	Wing Span ft. (m.)	Wing Area ft.^{2} (m.^{2})	Aspect Ratio	Empty Wt. lbs. (kg.)	Loaded Wt. lbs. (kg.)	Wing Loading lb/ft^2 (kg/m^2)	Reference
Haessler-Villinger "Mufli" Germany -/1935	44.3 (13.5)	104 (9.65)	18.8	81 (36.7)	246 (111.5)	2.37 (11.5)	9, 11, 17
Bossi-Bonomi "Pedaliante" Italy -/1936	55.8 (17.1)	230 (21.4)	13.4	215 (97.5)	358 (162)	1.56 (7.60)	17, 11
Southampton "SUMPAC" G. Brit. Nov./1961	80.0 (24.4)	300 (27.9)	21.3	128 (58.0)	269 (122)	0.89 (4.33)	14, 24, 11 16
Hatfield "Puffin I" G. Brit. Nov./1961	84.0 (25.6)	330 (30.7)	21.4	110 (49.9)	250 (113)	0.76 (3.70)	6, 11, 16
Hatfield "Puffin II" G. Brit. Aug./1965	93.0 (28.4)	390 (36.2)	22.0	136 (61.6)	265 (120)	0.68 (3.31)	7, 11, 17
Nihon U. "Linnet I" Japan Feb./1966	72.2 (22.0)	280 (26.0)	18.6	111.5 (50.6)	235 (106.5)	0.84 (4.09)	11
" " "Linnet II" Feb./1967	72.2 (22.0)	280 (26.0)	18.6	98.5 (44.7)	225 (102)	0.81 (3.94)	11
Weybridge G. Brit. -/1971	120.3 (367)	485 (45.0)	30.0	125 (56.7)	275 (124.5)	0.57 (2.78)	
Hertstordshire "Toucan" G. Brit. -/1971	123.0 (37.5)	600 (55.8)	25.0	145 (65.8)	445 (205)	0.74 (3.60)	11
Southend "May fly" G. Brit. (No flights) 1964	90.0 (27.4)	405 (37.6)	20.0	146 (66.2)	438 (198.5)	1.08 (5.25)	16, 10, 11
Ottawa Canada -/1972	90.0 (27.4)	450 (41.8)	18.0	165 (74.8)	450 (204)	1.00 (4.87)	5, 10, 11

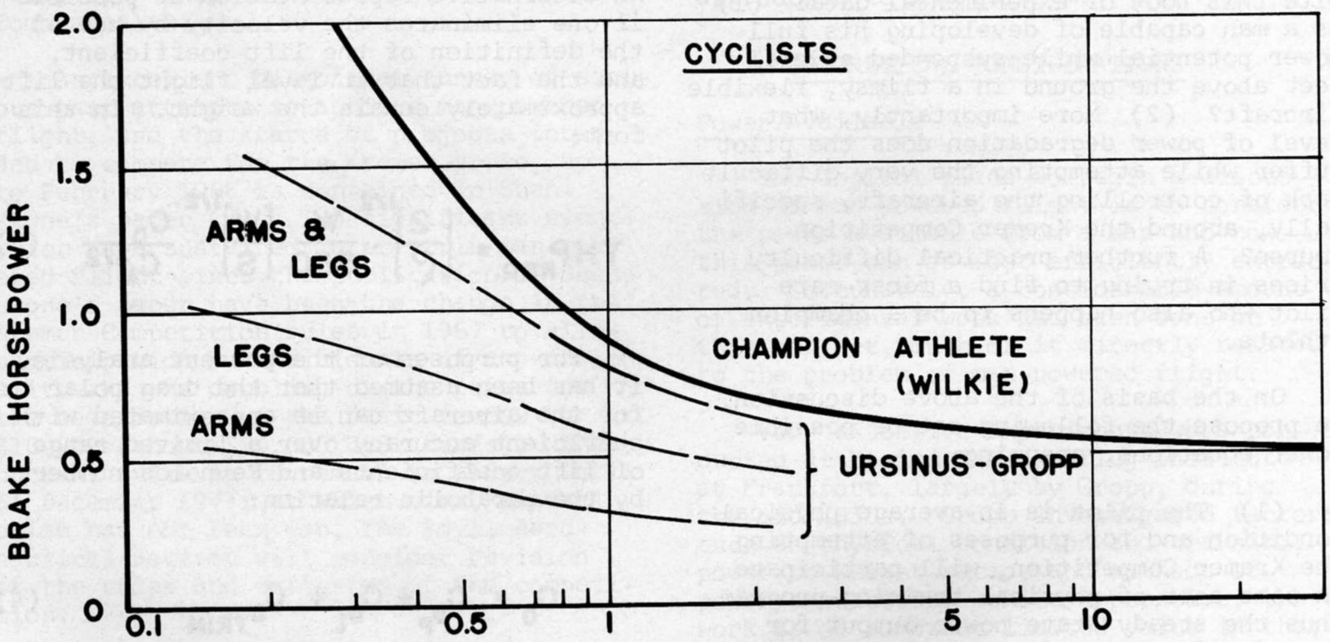


FIGURE 1. STEADY STATE POWER AVAILABLE FROM CYCLISTS

Using this approximation, one obtains the usual results that:

$$C_{D_0} = \frac{K C_L^2}{\pi AR} \quad \text{for L/D max (max glide angle)}$$

(5)

$$C_{D_0} = \frac{K C_L^2}{3\pi AR} \quad \text{for minimum power (minimum sink rate)}$$

Now, taking Eqs. 2, 4, and 5 together and introducing the specific power P, we may write (in the English system of units):

$$P = C_1 \left[\frac{W}{S}\right]^{1/2} \frac{C_L^{1/2}}{AR_e} = C_2 \left[\frac{W}{S}\right]^{1/2} \frac{C_{D_0}^{1/4}}{AR_e^{3/4}} \quad (6)$$

$C_1 = 0.0306$ $C_2 = 0.0408$ for max L/D

$C_1 = 0.0204$ $C_2 = 0.0358$ for min.power

Figures 2 and 3 show plots of the quantity: specific power/(wing loading)$^{\frac{1}{2}}$ as a function of lift coefficient. These figures, together with appropriate relationships for aircraft weight, power available, and effective aspect ratio (subject to constraints on realizable lift coefficients and corresponding drag values) form the basis of a sizing study of man-powered aircraft. In order to get a feel for the numbers, the regions on Figs. 2 and 3 which apply to modern Standard Class and several recent types of Open Class sailplanes (5, 6) are shown together with the general location of several existing man-powered aircraft.[1] It should be pointed out that, aside from the assumption that the aircraft has a parabolic drag polar, Figs. 2 and 3 are completely general.

Propeller and Transmission

No really satisfactory analysis of man-powered aircraft propeller and transmission efficiencies has been published, although on the basis of the discussion in Ref. 7 and experience with the Puffin aircraft, it appears that values greater than 80 percent are achievable. For purposes of the present analysis, a value for η of 0.80 was selected as a conservative estimate.

Weights

As a result of the experience gained by various groups from the actual construction of successful man-powered aircraft, it is now possible to estimate achievable weights for new designs with considerably more assurance than has been possible in the past. Single place aircraft of very large size, and empty weights on the order of 100-120 lb (50-55 kg) with adequate load factors have been demonstrated. These machines have not relied on the extensive use of exotic materials and structural techniques. In fact, of those machines completed, the structural approach may be considered quite conservative considering the design problem faced. With the exception of the Linnet series in Japan, for example, little use has been made of materials such as rigid foams, Fibreglas, etc. It seems probable that use of these and other new materials offer considerable promise of even further weight reduction if intelligently used. In addition, the use of such materials as rigid foam offers potential time and cost savings which could be of very great benefit to a small group with limited resources.

From the data in Table 1, it is possible to specify some simple, realistic weight equations for an aircraft sizing analysis. If one assumes, in the absence of modern data on optimum human power-to-weight ratios, that the average crew member weighs 140 lb (64 kg), the following equations for gross weight are proposed:

[1] In order to place sailplanes on the diagrams, the following relation has been used: $P = \dot{z}/550$ where $\dot{z}$ is the sink speed in ft/sec

[2] It may be objected that the proposed weight equations take no explicit account of variations in weight with aircraft size parameters. The approximations are legitimate if one considers the resulting weights as design goals, and the resulting size parameters (e.g., wing span, aspect ratio) are within the general range of applicability of the particular equation used. The justifications for specifying the weight in the form chosen are: (1) arithmetic expediency; (2) the resulting weights agree

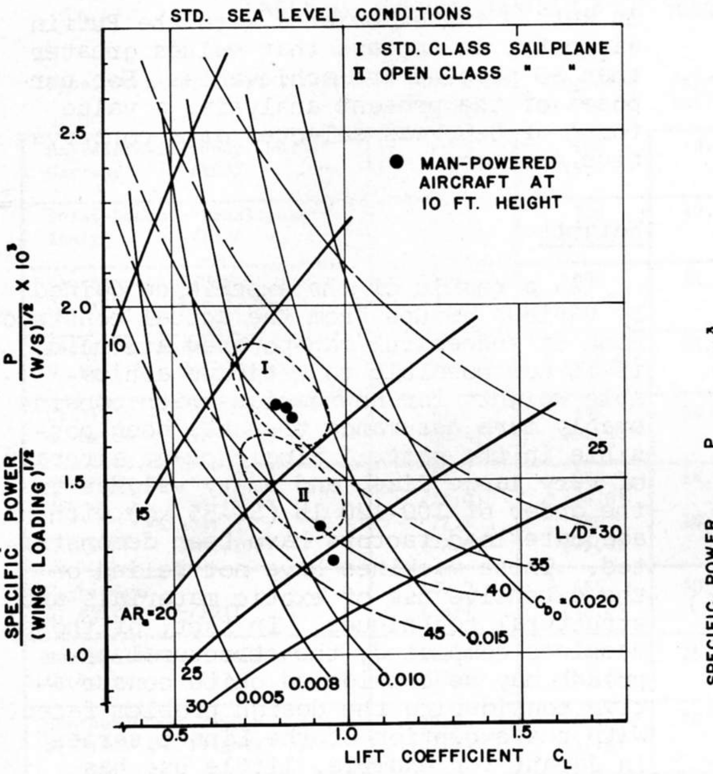


FIGURE 2. VARIATION OF SPECIFIC POWER REQUIRED WITH LIFT COEFFICIENT AND WING LOADING FOR LEVEL FLIGHT AT MAXIMUM LIFT/DRAG RATIO

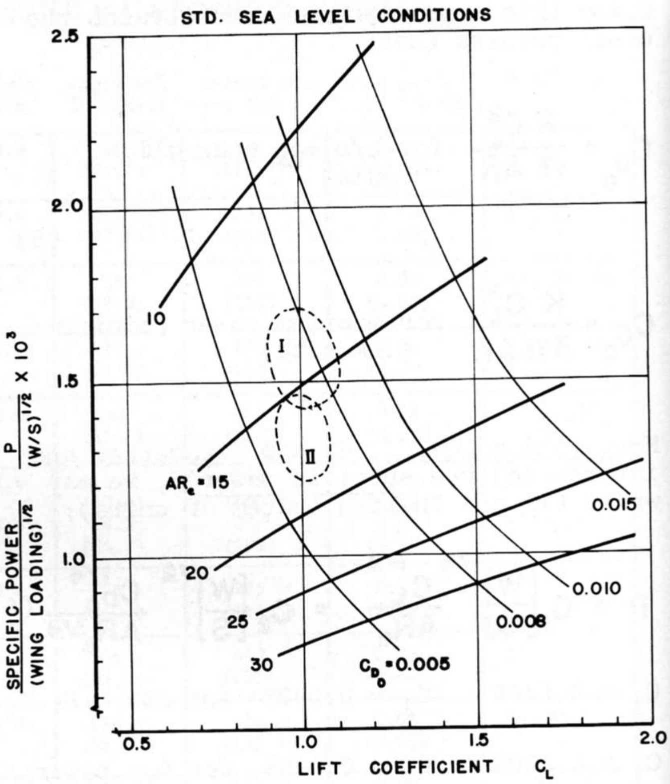
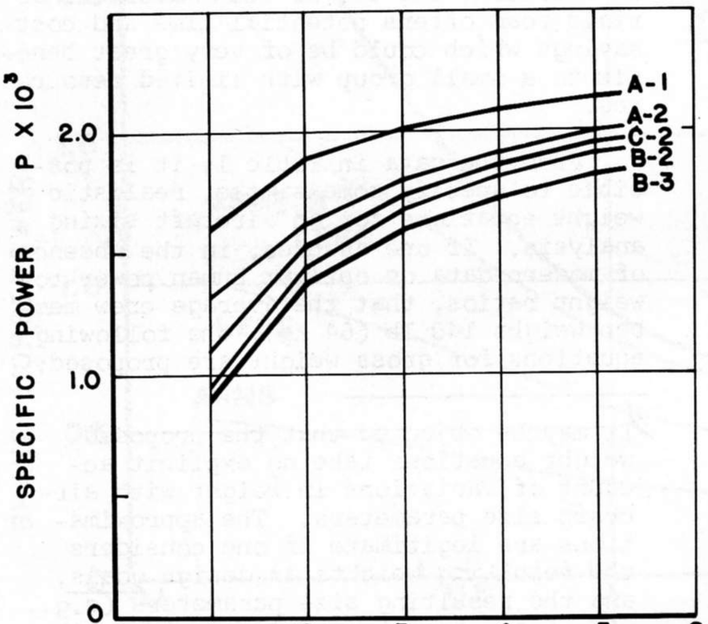


FIGURE 3. VARIATION OF MINIMUM SPECIFIC POWER REQUIRED WITH LIFT COEFFICIENT AND WING LOADING



POWER EQUATIONS:

A. $THP = 0.4\,N - 0.08$

B. $THP = 0.4\,N - 0.16$

C. $THP = 0.4\,N - 0.12$

WEIGHT EQUATIONS:

1. $W = 140N - 60N^{0.73}$
2. $W = 140N - 115\,N^{0.50}$
3. $W = 140N - 125\,N^{0.56}$

FIGURE 4. SPECIFIC POWER AVAILABLE AS A FUNCTION OF THE NUMBER NUMBER OF CREW

$W = 140\ N + 60\ N^{0.73}$ 7.1
Optimistic, Small Aircraft

$W = 140\ N + 115\ N^{0.50}$ 7.2
Present state-of-the-art

$W = 140\ N + 125\ N^{0.56}$ 7.3
Pessimistic, Large Aircraft

Equation 7.2, for example, gives a weight of 255 lb (115 kg) for a one-man machine; 445 lb (220 kg) for a two-place aircraft; 620 lb (280 kg) for a crew of three, and so on. Now combining Eq. 7 with Eq. 1, assuming $\eta = 0.8$, a plot of specific power available as a function of the number of crew members can be made, as shown in Fig. 4. The important conclusion to be drawn from Fig. 4 is that regardless of the optimism or pessimism of the weight and power available estimates, a clear gain in available specific power is achieved by increasing the crew size from one to two. The specific power available continues to increase with increasing crew size; however, the curves begin to flatten after a crew size of two men has been reached and it seems unprofitable to consider aircraft with crews of more than three or four men. The full importance of the above conclusions should become clear in the later analysis when the geometric size of the aircraft is considered. For comparison with Figs. 2 and 3, it is convenient to plot the quantity: specific power available divided by the square root of the wing loading, against wing loading for various values of crew size. A representative graph of this sort using Eqs. 1.3 and 7.2 is shown in Fig. 5. Figure 5 shows that at a given level of available $P/(W/S)^{\frac{1}{2}}$, the allowable wing loading increases with an increase in crew size, the largest jump again occurring between a one-man and a two-man crew.

GROUND EFFECT AND EFFECTIVE ASPECT RATIO

A brief comparison of Figs. 2, 3, and 5 shows that unless the wing loading and/or the weight are kept low, or the effective aspect ratio is very large, true man-powered flight is nearly impossible.

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satisfactorily with data in Table 1; and (3) the equations are sufficiently realistic to demonstrate the salient points to be brought out in the succeeding analysis.

Fortunately, the Kremer Competition rules specify that the aircraft cross the starting and finishing line at an altitude of only 10 ft (3.0 m). Thus if the span of the wing is sufficiently large, a considerable increase in effective aspect ratio may be obtained from ground effect. The augmentation of aspect ratio shown in Fig. 6 is expressed as a function of the ratio of the height of the a.c. of the M.A.C. of the wing to the geometric wing span. The values shown in Fig. 6 have been substantiated (8) for wings with aspect ratios up to about 8. No reference has been found, however, for ground effect augmentations for wings with aspect ratios customarily used on high-performance sailplanes and existing man-powered aircraft.

In order to study the wing size required for a man-powered aircraft, it is necessary to have an estimate of the effective aspect ratio corresponding to the purely geometric aspect ratio. The AR_e is defined by Eq. 4. Despite the limitations of the parabolic polar, it has been found that on the basis of drag data from flight tests of twenty sailplanes (5, 6), a reasonable correlation exists between the k factor for the total airplane and the wing geometric aspect ratio (for flight outside of ground effect), if proper account is taken of Reynolds numbers and aircraft layout. From this information, it is possible, by adjustment of the Reynolds numbers down to the range anticipated for man-powered aircraft, to estimate the appropriate k values as a function of aspect ratio, assuming airfoils with drag characteristics similar to the Wortmann series (9, 10). It is further assumed that the factor $k_{W\infty}$ (k_W outside of ground effect) has a value of 1.05.

For purposes of the present paper, the values of AR_e at an altitude of 15 ft (4.6 m) (assuming the bottom of the aircraft is 10 ft (3.0 m) above the bottom of the aircraft) are shown in Fig. 7 with values of geometric aspect ratio used as a parameter. The generating equation for Fig. 7 is:

$$AR_e = \frac{AR}{K} \quad (8a)$$

$$AR = b^2/S \quad (8b)$$

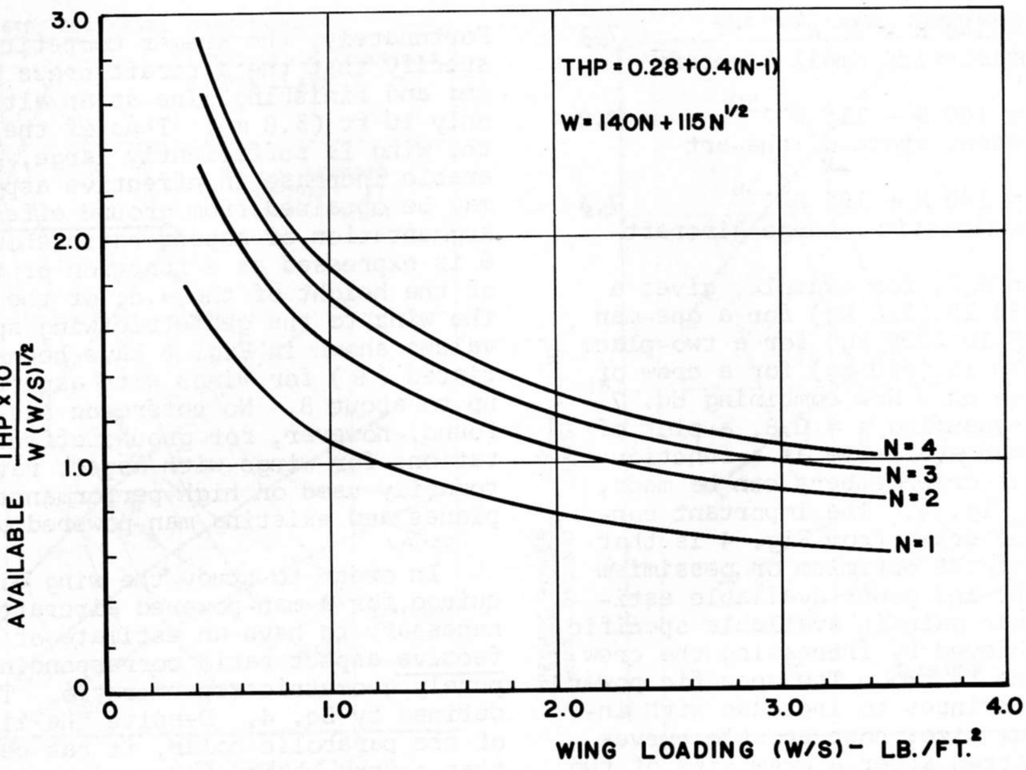

FIGURE 5. TYPICAL VARIATION OF THE PARAMETER $P/(W/S)^{1/2}$ AVAILABLE AS A FUNCTION OF CREW SIZE AND WING LOADING.

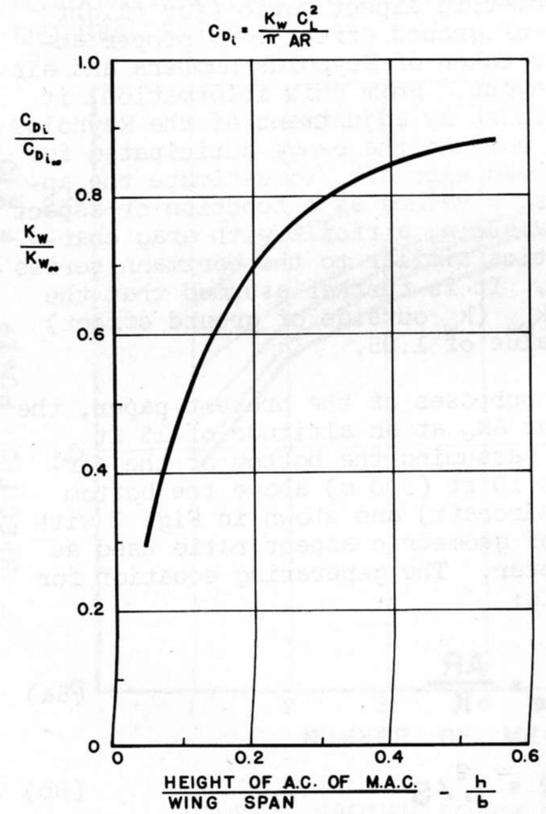

FIGURE 6. THE INFLUENCE OF GROUND PROXIMITY ON WING INDUCED DRAG

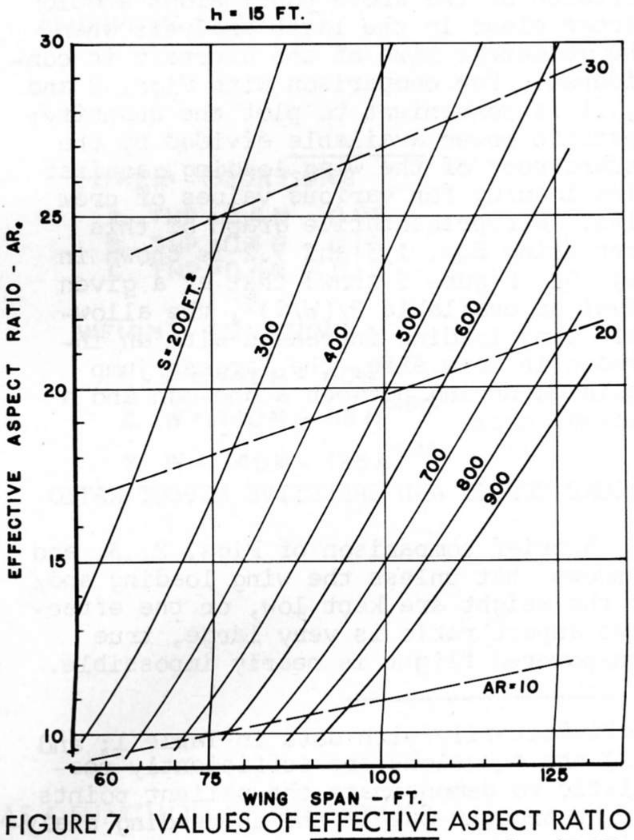

FIGURE 7. VALUES OF EFFECTIVE ASPECT RATIO AS A FUNCTION OF WING SPAN AT h = 15 FT ABOVE THE GROUND

$$K = (0.01\,AR + 0.18) + 1.05\,\frac{K_W}{K_{W_\infty}} \quad (8c)$$

(for $\frac{K_W}{K_{W_\infty}}$ see Fig. 6)

These values of effective aspect ratio are considered to be representative of those attainable with an aircraft similar in layout to a conventional high-performance sailplane but having a relatively bulky fuselage.

It is worth noting that on the basis of the work of Cone (11,12,13), it appears that values of k_{w_∞} substantially less than unity have been achieved by some soaring birds. This effect has apparently been obtained through the use of a combination of spanwise camber and what may be described as flexible vaned panels near the tip of the birds' wings. Such devices deserve extensive investigation, particularly for possible application to "one-point design" aircraft such as the man-powered aircraft.

TURN PERFORMANCE

Spillman (14) has presented a good preliminary analysis of the difficulties to be anticipated in attempting to make the turns required to negotiate the Kremer course. The major difficulties are the adverse roll and yaw moments (and consequent large values of trim drag and required aileron power) produced when operating a very large span, lightweight aircraft in a banked turn close to the ground. The nature of the problem can be illustrated by considering some of the numerical results of Spillman's analysis. The major variables influencing the turning performance (assuming a steady, constant altitude turn) are the wing span, speed, altitude, and bank angle. The turn performance is also limited by the maximum available section lift coefficient of the wing. Consider an aircraft traveling with a centerline velocity of 30 ft/sec (9 m./s.) at an altitude of 15 ft (4.6 m.), measured to the height of the M.A.C. in level flight. Referring to Fig. 8 for notation, values of various turn parameters are given in Table 2 for aircraft with spans of 60 ft (18 m.); 75 ft (23 m.); and 90 ft (27 m.) at bank angles of 2, 5, and 10 deg.

The information in Table 2 indicates the following difficulties in performing the turns:

1. When the wing span of the aircraft becomes a significant percentage of the turn radius, the wing begins to behave like a rotor. Increasing bank angle leads to smaller turn radii and to an increase in the difference in velocity acting on each section of wing across the span. For example, with the 90 ft (27 m.) span wing in a 10 deg bank, the outer wing tip is traveling almost twice as fast as the inner tip. For this case, assuming no aileron deflection, the difference between the actual spanwise airload and the corresponding ideal elliptic distribution is shown superimposed in Fig. 8. This demonstrates the nature of the spanwise shift in center of pressure which leads to the production of an adverse rolling moment. Very large values of aileron power may be required; values which cannot be produced without excessively large ailerons. In addition, the resulting non-optimum lift distribution leads to an increase in induced drag, which contributes to an increase in power required to make a turn.

2. In addition to the usual problem of aileron drag (if conventional ailerons are used for roll control) producing an adverse yaw, differential ground effect must be considered when the aircraft is operated close to the ground. The average altitude of the lower semi-span of the wing (depending on the bank angle and wing span) may be well below the height of the outer (upper) semi-span. This leads to a difference in ground effect on the two wing panels, which tends to aggravate the adverse yaw tendency. This may lead to the requirement for a very large rudder and/or excessive trim drag, both of which tend to increase power required in the turn.

ANALYSIS

No claim is made for the absolute accuracy of the preceding data on weight, power available, or aspect ratio/ground effect; each of these topics deserve detailed attention in separate papers. However, the information presented appears to be, on the basis of experience with the man-powered aircraft built and flown to date, sufficiently correct to allow some qualitative conclusions to be drawn regarding design goals for future aircraft of this type.

Despite the demonstrated feasibility (by the Southampton, Hatfield, and Nihon machines) to fly, including the ability to make unaided man-powered takeoffs and controlled turns, by muscle power alone, the Kremer prize has yet to be won and is apparently not close to being won by existing machines. Part of the difficulty becomes apparent in a brief examination of the aircraft characteristics contained in Table 1.

The Puffin II aircraft, for example, has a wing span which is about 50 percent greater than conventional Open Class sailplanes, but the machine weighs less than a third as much. It seems intuitively clear that operating such a vehicle, particularly in a banked turn very close to the ground, must be very difficult. In fact, several references on existing man-powered aircraft have commented on the very poor handling characteristics of these machines relative to conventional aircraft and sailplanes (see especially Ref.15, by Piggott).

It is clear from the previous discussion of turn performance, that the handling characteristics of man-powered aircraft would be greatly improved if the size (particularly the wing span) could be substantially reduced. It is our opinion that the single most important factor in the failure of all past attempts to win the Kremer prize has been the very large wing spans of the aircraft involved. In retrospect, it seems that the benefits of a large wing span in increased effective aspect ratio by ground effect augmentation have been largely cancelled by the structural and turn performance problems which such spans have introduced.

One can further speculate that several of the following problems may also modify the theoretically achievable performance of the aircraft:

1. Aeroelastic distortion (particularly wing torsion) of the very lightweight structures.

2. Distortion of the airfoil contours under airloads due to the use of non-rigid covering for the wing surfaces.

3. Less than optimum power output from the pilot due to fatigue and distraction.

It should be noted that most of the above listed difficulties are, in part, related to the size problem previously discussed.

Accepting the assertion that it would be very beneficial to reduce the wing spans of man-powered aircraft from their present values, let us examine how this might be accomplished. For purposes of this discussion, consider a family of geometrically similar aircraft with up to four crew members as shown in Fig. 9. Two optimum design conditions are considered here: A family of aircraft designed to the condition of L/D_{max} with an assumed value of $C_{D_o} = 0.012$, when airfoils without high-lift devices are employed, and a family designed to the condition of minimum power, with $C_{D_o} = 0.015$ when flaps are used. With the data on power available, weight, and aspect ratio presented in the previous section, combined with the general sizing diagrams, Figs. 2 and 3, the reference aircraft have the characteristics listed in Table 3.

Three factors in Table 3 are important:

1. The wings of both the two- and three-man machines are slightly <u>smaller</u> than those of a one-man machine.

2. The wing areas of the aircraft designed to the condition of minimum power are larger than those of the aircraft designed for L/D_{max}. However, the difference in the wing spans between aircraft with the same crew size designed to the two conditions, is relatively small.

3. The cruise speeds of the aircraft designed for L/D_{max} are substantially higher than those for the corresponding aircraft designed for the condition of minimum power.

If one wishes to reduce the wing span of the aircraft listed in Table 3, the aspect ratio and/or the wing area must be reduced. On the basis of Fig. 2 and 3, one way this might be accomplished is by very careful design, and perhaps even resorting to limited boundary layer control, to reduce the value of C_{D_o}. If, however, one assumes that C_{D_o} can be varied only slightly for a given aircraft

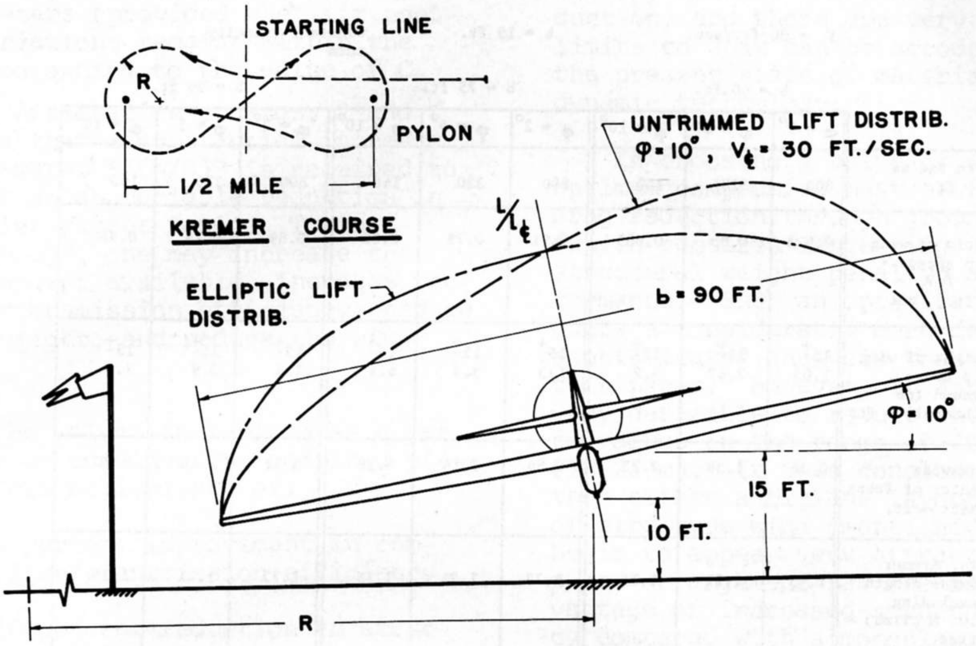

FIGURE 8. NOTATION AND TYPICAL INFLUENCE ON WING SPANWISE LOAD DISTRIBUTION FOR LOW-SPEED TURNING FLIGHT CLOSE TO THE GROUND

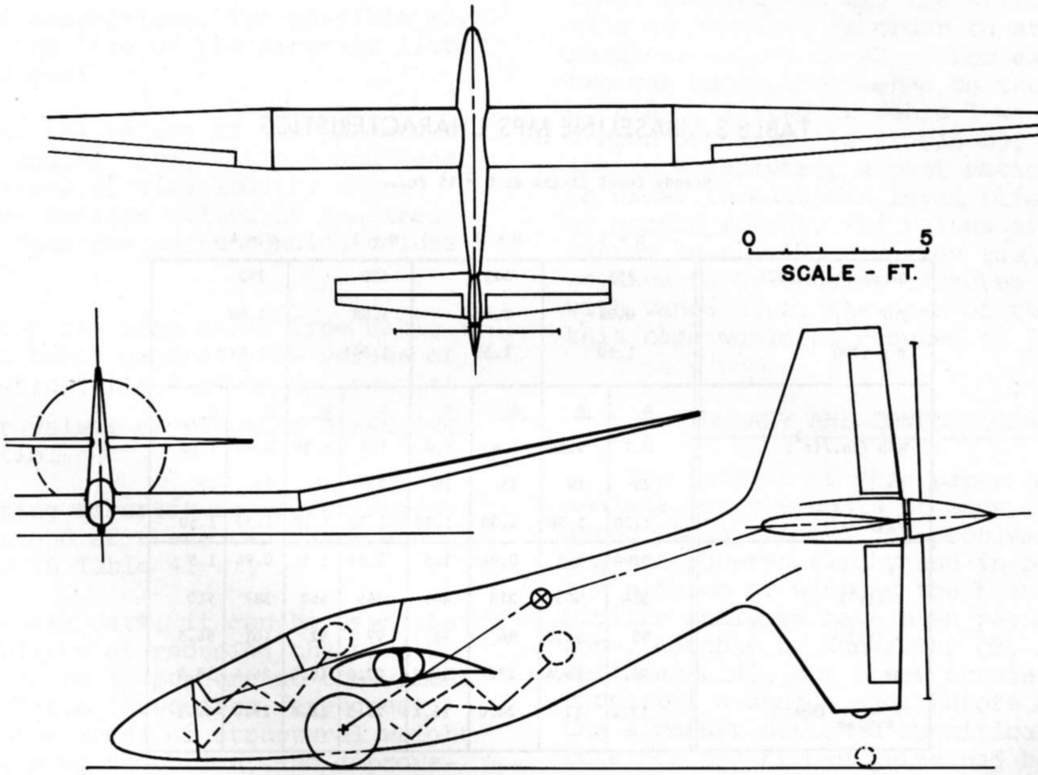

FIGURE 9. TYPICAL TWO-PLACE HIGH PERFORMANCE MAN-POWERED AIRCRAFT (THE GREAT SPECKLED BIRD)

TABLE 2. TURN PERFORMANCE

V = 30 ft./sec. h = 15 ft. Constant velocity turn

	b = 60 ft.			b = 75 ft.			b = 90 ft.		
	$\varphi = 2^o$	$\varphi = 5^o$	$\varphi = 10^o$	$\varphi = 2^o$	$\varphi = 5^o$	$\varphi = 10^o$	$\varphi = 2^o$	$\varphi = 5^o$	$\varphi = 10^o$
Turn Radius R ~ ft.	800	320	160	800	320	160	800	320	160
Ratio of wing tip speeds - $V_{t_{in}} / V_{t_{out}}$	0.925	0.83	0.685	0.91	0.79	0.62	0.89	0.75	0.56
Height of wing tip above ground (no dihedral) ~ ft.	15 ± 1.05	15 ± 2.62	15 ± 5.2	15 ± 1.3	15 ± 3.3	15 ± 6.5	15 ± 1.6	15 ± 3.9	15 ± 7.8
Spanwise Center of Press. Shift ~ ft.	0.36	1.38	2.73	0.86	2.14	4.32	1.22	3.10	6.20
Min. Kremer Course length (excluding T.O. & climb) ~ miles	1.73	1.21	1.15	1.73	1.21	1.15	1.73	1.21	1.15
Time around Kremer Course = minutes.	5.1	3.56	3.38	5.1	3.56	3.38	5.1	3.56	3.38

TABLE 3. BASELINE MPS CHARACTERISTICS

Steady level flight at h = 15 ft.

	N = 1		N = 2		N = 3		N = 4	
Gross Wt. (lbs.)	255		445		620		790	
THP_{avail}	0.28		0.68		1.08		1.48	
P x 1000	1.10		1.53		1.745		1.875	
	A	B	A	B	A	B	A	B
W/S (lb./ft^2)	0.7	0.55	1.4	1.0	1.8	1.35	2.04	1.55
AR_e	25	18	25	18	25	18	25	18
$P/(W/S)^{\frac{1}{2}}$	1.30	1.50	1.30	1.50	1.30	1.50	1.30	1.50
C_L	0.94	1.5	0.94	1.5	0.94	1.5	0.94	1.5
S (ft^2)	364	465	318	445	345	460	387	510
b (ft)	99	92.5	94	91	97	92	101	96.5
AR	26.9	18.4	27.7	18.5	27.2	18.4	26.4	18.2
V_{cruise} (mph.)	17.1	12	24.0	16.1	27.3	18.8	29.0	20.1

A. Max. L/D design.

B. Min. Power design.

configuration, over a reasonable range of size parameters (provided the lift coefficient variations remains within the range corresponding to the value of C_{D_o} selected), examination of Figs. 2 and 3 indicates that a substantial increase in the parameter $P/(W/S)^{\frac{1}{2}}$ is required to bring about an appreciable reduction in the effective aspect ratio. To increase $P/(W/S)^{\frac{1}{2}}$, one may increase the brake horsepower available, increase the propeller/transmission efficiency, reduce the gross weight, and reduce the wing loading.

Using the values in Table 3 as a reference, let us consider the combined effect (or their equivalent) of:

1. A 3 percent improvement in combined propeller/transmission efficiency.

2. A 10 percent reduction in structural weight.

3. Careful selection and training of pilot and crew members such that crews with an average weight of 130 lb (59 kg) per man, without degradation of power output, can be provided.

With these assumptions, two possible ways to reduce the size of the aircraft listed in Table 3 are:

1. Use the values of the parameter $P/(W/S)^{\frac{1}{2}}$, and AR_e from Table 3 and generate new values of wing loading which should give smaller values of required wing area than the corresponding values in Table 3.

2. Keep the wing areas from Table 3 fixed, and hence generate new values of $P/(W/S)^{\frac{1}{2}}$ which, for a given C_{D_o} results in smaller values of required effective aspect ratio.

The resulting aircraft characteristics for the second of these two cases are summarized in Table 4.

From these data, it can be seen that the possibility of reducing the span by more than 10 to 15 percent of the values listed in Table 3 requires very great effort in the areas of structural weight reduction, drag reduction, and improvement in propeller/transmission efficiency. This must be considered the "conventional" approach to the problem of size reduction, and there are very definite limits to what can be accomplished given the present state of material and aerodynamic technology.

In choosing a value of wing span, an optimum compromise must be found between drag reduction through ground effect (which requires large wing spans with a structural weight penalty) and turn performance. Such an optimization would require a considerably more detailed and sophisticated analysis than presented in this paper. However, it appears to be very desirable to reduce the wing span to values in the range of 60 to 75 ft (18-23 m). If this conclusion is correct, then either a biplane layout or some sort of bird-type wing (mentioned previously) begin to appear very attractive. The biplane arrangement has the additional advantage of increased structural efficiency compared with a monoplane.

A further point, with respect to the bird-type wing, is that if one ever hopes to build an aircraft of this type, with a conventional wing, capable of operating out of ground effect by man-power alone, values of AR substantially higher than those required to fly the Kremer course will be required in order to attain the required values of AR_e. For example, the two-man machine designed to the condition of L/D_{max} listed in Table 3 would require a span of about 114 ft (35 m), corresponding to a geometric aspect ratio of 41.0 in order to maintain level flight outside of ground effect. If values of the k-factor in the AR_e equation could be decreased to 0.75 using cambered span wings with vaned tips, the span of the wing in this case would be reduced to 99 ft (30 m).

SUMMARY AND CONCLUSIONS

The purpose of this paper has been to analyze, on the basis of some first order aerodynamic theory, the problem of achieving man-powered flight and in particular the problem of winning the Kremer prize. Similar analyses have been performed before, notably by Nonweiler (2, 3) and Spillman (14), but these studies were completed a decade ago, before any of the aircraft designed specifically to compete for the Kremer prize had been completed. Since then, a great deal of practical experience in design, construction, and flight has been gained, mainly by

TABLE 4. CHARACTERISTICS OF IMPROVED MPAs

Steady Level Flight at h = 15 ft.

	N = 1		N = 2		N = 3		N = 4	
Gross Wt. (lbs)	233.5		408		570		727	
THP_{avail}	0.29		0.707		1.21		1.535	
P x 1000	1.245		1.730		1.965		2.110	
	A	B	A	B	A	B	A	B
S $(ft.^2)$	364	465	318	445	345	460	387	510
W/S $(lb./ft^2)$	0.64	0.506	1.285	0.92	1.65	1.24	1.875	1.425
$P/(W/S)^{\frac{1}{2}}$	1.555	1.75	1.53	1.80	1.53	1.77	1.53	1.77
C_{D_o}	0.012	0.015	0.012	0.015	0.012	0.015	0.012	0.015
AR_e	20	14	20	14	20	14	20	14
b (ft)	88.5	81.5	84	80	86.5	81	90.5	85
C_L	0.83	1.2	0.83	1.2	0.83	1.2	0.83	1.2
AR	21.5	14.3	22.2	14.4	21.7	14.3	21.1	14.2
b_{ref} (Table 3) (ft)	99	92.5	94	91	97	92	101	96.5
$\Delta b/b_{ref}$	10.6%	11.4%	10.7%	12.1%	10.8%	12%	10.4%	11.9%

A. Max. L/D design.

B. Min. Power design.

groups in Britain and in Japan. On the basis of this experience, it has been possible to reassess the problems involved in achieving true man-powered flight. The main conclusions of this study are:

1. On the basis of simple theory, and data on modern sailplanes and existing man-powered aircraft, it appears that man-powered flight of sustained duration in a straight line at low altitudes (on the order of 10 to 20 ft (3-6 m) is readily achievable with a carefully designed aircraft flown by a pilot in good physical condition. In addition, a sufficient margin of power exists to overcome a reasonable drag increase during flight in a banked turn. Flight outside of ground effect presents a very much more difficult problem, and if conventional wing design techniques are used, would require an aircraft with an extremely high aspect ratio and wing span.

2. The major problem with existing aircraft constructed to compete for the Kremer prize is their great size relative to their very low weight, coupled with corresponding very low flight speeds, and operation at very low altitude; this results in very poor handling characteristics, particularly in banked turning flight. Chances of winning the Kremer prize would be greatly enhanced if the size--especially the wing span--could be substantially reduced. Values of wing span in the range of 60 to 75 ft (18-23 m) are considered a desirable design goal. The optimum value of wing span must be determined by a very careful analysis of the tradeoffs between turn performance, ground effect, and weight.

3. There is an advantage in using at least a two-man crew. Based on the assumptions made here, both the two- and three-man machines are smaller than the corresponding single-place aircraft. This is due simply to the fact that by doubling the number of crew members the power available more than doubles, but with careful structural design the weight should not double. It is unfortunate that no two-man machine has yet flown to provide verification of this conclusion.

4. A conventional approach to size reduction through weight reduction and increased propeller/transmission efficiency seems to offer only limited possibilities. Based on presently foreseeable structural and materials technology, our analysis indicates that wings with spans greater than 70 ft (21 m) would be required for aircraft intended to compete for the Kremer prize. Reductions in span below this limit would require use of more exotic aerodynamic techniques. Among the possibilities which should be investigated in much more detail are:

a. A biplane configuration.

b. The augmentation in effective aspect ratio achieved by some soaring birds, and the ways in which aerodynamically equivalent structures might be built.

c. The tradeoffs between power required and performance of aircraft using limited boundary layer control for drag reduction.

5. Despite the limited potential for size reduction by means of weight reduction, and improvements in mechanical efficiency, weight, and power available are still two of the most important parameters in the design problem. Any reduction in weight achieved must be considered a net gain. Similarly, increases in propeller/transmission efficiency are equivalent to a significant reduction in weight or increase in power available. Thus major efforts should be made in any future designs to make substantial improvements in these areas.

It our opinion that the Kremer prize can be won and that efforts to do so may produce technological gains of great significance to other branches of aviation. Considerable work still needs to be done in the areas of very low speed aerodynamics and ultra-low density structures. The applications of this type of technology to sailplanes (powered and unpowered), light aircraft with STOL capabilities, etc., are quite clear. Perhaps competition for the Kremer prize will capture the imagination of a sufficient number of people to make large gains in this technology possible. One gets the definite impression, after surveying the literature on man-powered flight, that with just a little more effort by enough individuals, and with some improvements in key areas of existing designs, the dream of achieving true man-powered flight will be turned into reality. Whether this is true or merely an illusion remains to be demonstrated.

RECOMMENDATIONS

In light of the analysis presented in this paper and a fairly extensive survey of the literature on man-powered flight and related areas, we recommend the following:

1. A flight test program should be undertaken, using a suitable aircraft, such as a powered sailplane, to investigate various aspects of flying the Kremer course, It is suggested that the aircraft fly the basic figure-eight course at very low altitude with the distance between the pylons distorted to account for the difference in speed range between the test aircraft and representative man-powered aircraft. The flight tests should examine the effects on handling characteristics on varying the bank angle, and the influence of altitude on ground effect, particularly in turning flight. Such a program would also be of value in training a pilot for an attempt at the Kremer prize prior to committing the actual man-powered machine to the task and risking possible damage.

2. An international man-powered aircraft society should be formed to open lines of communication, on an international level, between individuals and groups interested in man-powered flight, to encourage efforts to win the Kremer (or an alternative) prize, and to serve as a source of technical data for those interested in designing and/or building a man-powered aircraft.

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