# AIRWORTHINESS OF HUMAN POWERED AIRCRAFT FOR SPORT IN NEAR GROUND TURBULENCE

**by J.C.Wimpenny**

## 1. INTRODUCTION

The Rules and Regulations[1] in the HPAS competition call for safe operation in light to moderate winds and compliance with Airworthiness Requirements as and when they become established. The standard of performance and control implicit in the competition represents a judicious compromise between opportunity for fit individuals to fly reasonably often and the technological constraints of HPAS design. *The crucial progress needed lies in achieving safe operation by significant numbers of pilots in higher wind speeds than has been feasible to date.* This paper reviews this problem and makes comparisons with previous HPAS aircraft and their closest 'cousins' -Sailplanes and Hang Gliders. Recommendations for work in the near future are made to ensure that airworthiness requirements are available in good time.

## 2. THE COMPETITION SPECIFICATION

The weather conditions and performance requirements were determined as follows:-

**COURSE**

The triangular course totalling 1500 metres was chosen to emphasise speed performance, ready site availability and powerful turning ability.

**POWER REQUIRED vs: DESIGN AIRSPEED**

Handling, weather tolerance, robustness, ease of ground handling and road transport all improve rapidly as the design flying speed is increased. These improvements stem mainly from the corresponding reduction in wing span. The upper limit depends on the power capability of likely participants in the new sport; the aim being to widen involvement far beyond that achieved to date and so provide the basis for viable commercial development.

The presumed aircraft performance corresponds to the current state of art, e.g.(Musculair, Daedalus, Airglow) but with extra weight and drag for the greater strength, handling and robustness demands of HPAS, viz: a doubling of wing strength and stiffness and a 15% increase in total aircraft drag. The estimated power requirements and wing spans versus design speed are shown in Fig: 1.

**POWER AVAILABLE**

Early information from Wilkie[2] and Evans[3] indicates a 30% power difference between persons of good normal fitness and champion athletes. To quantify this, the spread in capability in the population is assumed to follow a normal distribution. The peak corresponds to the proportion of the population with good normal fitness; the champion athletes are the much smaller proportion with 30% more power. Two plausible values of their ratio have been assumed, a reliable value could be obtained from investigation. Fig:2 shows the cumulative eligibility of the fit population for participation in HPAS as a function of their power capability. The complete range of aerobic power available including the effect of flight duration is shown in Fig:3.The datum power level labelled normal fit is taken from Wilkie[2] as still the best information source.

**WIND STRENGTH DISTRIBUTION**

The competition requires the course to be flown in a mean wind of not less than 5.0 metres/sec (11.2 m.p.h.). This value has been derived from ESDU[4] data sheets which tabulate mean wind and gust speeds as a function of location, terrain roughness (local and upwind), height above ground and frequency of occurrence. The occurrence distribution for four types of site of interest for HPAS flying are shown in Fig:4 including the effect of height above ground. Any desired percentage of flyable days in the year may be selected and the corresponding wind speed can then be used in investigating flight performace and handling round the course. The corresponding gust information is given in Fig:5, from which the typical maximum gust in any hour is seen to be about 50% of the mean wind speed.

**COMPETITION PERFORMANCE CHOICE**

The interactions between the preceding parameters are displayed in Fig:6. This allows one to specify a desirable level of %days flyable and %eligibility within the fit population and the corresponding aircraft design speed. Alternatively,the aircraft may be specified and the corresponding flying days and pilot eligibility read off. The point chosen to specify the competition is indicated,viz: -

Terrain.-Large near flat field surrounded by mixed farmland.

49% days flyable

5 metres/sec (11.2 m.p.h.) mean wind speed

13% eligibility within the fit population, i.e.far more than the numbers of champion athletes.

Aircraft Design Flying Speed=10,5 metres/sec (23.5 m.p.h.). Corresponding wing span=18.8 metres (61.7 ft) at Aspect Ratio of 25.

Flight height 5.0 metres.

Time to fly course once (including wind and turn allowances)=3.4 mins.

## 3. AIRWORTHINESS ISSUES

**GENERAL POLICY**

HPAS will differ from preceding HPA's in three important respects. Firstly, they will be accessible to any person with the requisite athletic and flying skills, i.e. they will operate in the public domain. Secondly, whilst the competition only requires flight at low altitudes the flying speed is higher than on most previous aircraft and ,more significantly, they could be flown to heights from which an accident could prove fatal.Thirdly, flight in significant wind and the inevitable accompanying turbulence is a formal requirement bringing new demands on controllability. Thus, at an appropriate time, an Airworthiness Standard will need to be defined and endorsed in conjunction with established airworthiness organisations so that any responsible enthusiast can participate in the sport at an acceptably low risk. As sponsors of the HPAS Competition the R.Ae.S envisage liaising with the C.A.A. until an Airworthiness Standard is established.

**TECHNICAL PROBLEMS**

At.this stage of HPAS.affairs priority must be given to resolving feasibility problems, i.e.those whose solution is essential for the overall viability of the enterprise. There are also,of course, development problems but here, by definition, the means of solution are within the state of art,will be resolved by each competition entrant and prior research is not essential. The author's categorisation between feasibility and development problems is:-

**Feasibility**

- Design for full controllability and acceptable performance in the manoeuvres and wind strengths required in the competition.

**Development**

- Strength and stiffness provision with full allowances for aeroelastic effects (flutter, control reversal, divergence).
- Rigorous attention to drag minimisation.
- Stall and dive avoidance.
- Practicality, i.e. everyday robustness,repairability,assembly and stowage.
- Costs and Pricing implications.

Meeting these requirements will involve performance penalties so an allowance for increased weight and drag has been included in the perfomance shown in Fig: 1.
The rest of this paper considers the feasibility problem only, in line with the main aim of this Symposium.

## 4. CONTROL IN NEAR GROUND WIND and TURBULENCE.

### 4.1 CONTROL IN TURNS.

Two limitations affect HPAS, low rates of roll and a limit on bank angle. Both problems stem from the unique combination of large span and low flying speed. It is useful to compare HPAS with other Human Powered Aircraft and some more conventional types,as follows:-

**Rate of roll.**

Assuming conventional ailerons rate of roll is proportional to airspeed divided by wing span. Fig:7 shows that,if using ailerons, all human powered aircraft have low rates of roll,between about 20% and 50% of more conventional aircraft.

**Bank angle limitation in steady turns.**

In a steady co-ordinated turn the inner wing moves at a lower speed and the corresponding reduction in wing lift is restored by use of opposite aileron. With a HPA the low flying speed results in a small turning radius. This, combined with the large wing spans, gives an excessive loss of speed and lift on the inner wing which, at some critical bank angle, will exceed the countering ability of conventional ailerons. This could then lead to an uncontrollable spiral dive, particularly if accompanied by spiral instability. The questions arise-what determines the critical bank angle, and how can this situation be made safe?.

Fig:8 shows the critical bank angle,which is a unique function of $b/V^2$. Relevant aircraft are indicated and all HPA's are seen to have the lower values. Fig:9: shows the same information against speed and span and displays the very wide variations between aircraft types and within HPA's,- with HPAS and Musculair least affected.

**Achievable turn radius.**

The bank angle limitation has a major effect in increasing the minimum turn radius, thereby significantly reducing HPA manoeuvrability, as shown in Fig:10 .

**Turn co-ordination.**

In conventional aircraft turn entry is primarily by aileron, accompanied by a touch of rudder. At the relatively high lift coefficients and aspect ratios of HPA's aileron causes strong adverse yaw which necessitates much more countering rudder action. For very slow light HPA's like the Gossamer Condor[5] there is also a very large apparent mass which increases the effective roll inertia fivefold. Then the only satisactory technique was using yaw control alone to initiate the turn, roll control being used solely to hold off bank (birds use a similar technique). These problems ease somewhat at the higher HPAS speeds. However, they can only be understood and resolved by full dynamic control studies-open loop to examine aircraft stability and response, and closed loop work on the best type and usage of controls, including any novel possibilities.

**Course control.**

Assuming the above aspects are satisfactorily resolved the turn tasks in theHPAS competition can be reviewed. Two manoeuvres are essential for success in the new HPAS competition,viz; ability to track with precision, and to counteract the disturbing effect of side gusts. Good tracking is particularly important whilst turning round the competition course marker posts ***in a crosswind,*** also in the landing approach.These situations are now considered as follows:-

TURNS ROUND THE COMPETITION COURSE.

In principle turns in cross winds can follow a circular segment on the ground ,i.e.a circular track,or follow a circular path through the air, in which case the ground track is considerably distorted. Circular track turns require major changes in bank angle to offset the varying wind vector as the turn progresses. For a turn of radius twice the wing span the maximum bank needed is 37deg: with 1.25g. This bank far exceeds the safe limits and the variation in normal acceleration will give unnecessary drag. It seems therefore that it will be preferable to turn at a constant bank angle and accept the distortion in ground track. Fig:11 shows what is involved ,a task requiring skill but one whch should respond to practice.This situation has been recognised in formulating the competition by an allowance for the increased flight time involved.

SIDE GUST DISTURBANCES.

Human Powered Aircraft are particularly vulnerable to side gusts on account of their low flying speeds.This is most apparent when trying to stay within, for example, a perimeter track and especially so when preparing to land. It is useful therefore to examine.the ability to make small track corrections i.e.to perform an 'S' shaped track change.The most efficient *conventional* control technique for small corrections is to use a pulse of aileron until a useful bank is reached, followed immediately by reversal to zero bank. This can be increased until the peak bank reaches the safe critical value. At this point the HPA is suffering the combined constraints of low rate of roll and low maximum safe bank angle. If larger course changes are required the bank can be maintained at the safe limit for as long as desired,a relatively more efficient situation. This sequence of options is shown in Fig: 12 .

Comparative estimates, assuming perfect turn co-ordination, have been made between HPAS, Sailplanes and Hang Gliders (assuming pro tem that these behave as if fitted with ailerons.) These particular comparisons have the advantage of identifying separately the effects of span and speed changes and 'calibration' using practical Sailplane and Hang Glider experience. The results are shown in Figs:13 to 15 . It is seen that:-

HPAS has the best course change with bank angle (N.B for the pulse aileron deflection considered ) --Fig:13 .

HPAS has the slowest response,but is quite close to the sailplane --Fig:14.

HPAS track correction takes less distance than a sailplane but more than a hang glider Fig 15.

However,it must be emphasised that these results apply only to perfectly co-ordinated turns so should be taken as indications only at this stage.

Coming now to the side gust disturbance it would be useful to make a similar comparison between the three types of aircraft under consideration. A very preliminary comparison between HPAS and a sailplane is made in ref: 6 for a side gust velocity of 5 m.p.h.. Typical sideways track displacements of between 15ft and 30ft are estimated for HPAS and *these are twice the amounts of the sailplane.*Referring to Fig:15.their appears to be ample control power available to correct these sized displacements and indeed the greater manoeuvrability of the HPAS in the x-y plane also shown in Fig:15 could mean that that the overall correction capability of the.two types may not be that different -- except that everything takes up to twice as long with the HPAS. This may cause a problem of pilot perception of slow motion, especially with the random motions during gust interference (perhaps the visible canard on the Condor and Albatross was an advantage here ?). In view of the complexity of these problems, it is clear that a much fuller examination is needed.

**4.2 HEAD and TAIL GUSTS**

In the near ground flight regime of HPAS the gust structure is far from isotropic. The strongest gusts are along the direction of wind , followed by side gusts, with vertical gusts being limited by ground proximity to about half the strength of those along the wind. The spatial gust distribution is also important in affecting the aircraft response, there usually being a worst gust length particular to each aircraft type. It is apparent from every day observation that increases of wind speed tend to happen rather suddenly and then to persist for some time, so study of behaviour in a discrete gust encounter.has some value. Fig:16 , taken from ESDU[7] data sheets, shows the distribution of discrete gust strength vs: gust duration for.the presumed typical HPAS competition site.

Two aircraft responses are of greatest concern, increase in 'g' with a head gust,and loss of height in a tail gust. An upper limit to 'g' simply is the the peak velocity ratio squared, but the height loss calculation is rather more complicated. A sudden loss of airspeed excites a downward phughoid oscillation, involving a maximum height loss nearly twice the steady state loss deducable from energy conservation. Also, the worst case is when the time flying through the gust is equal to half the phughoid period. The resulting comparison between HPAS, Sailplane and Hang Glider is given in Fig:17 .The HPAS responds more quickly owing to the shorter phughoid period,and appears likely to experience larger wing loads. However the height losses shown for the sailplane and hang glider seem to be considerably larger than one would suppose is the case in practice .This could mean that the assumption of equal peak head and tail gusts is invalid. The matter requires further investigation starting with looking at actual wind speed traces for terrains of interest.

### 4.3 PROBLEM COMBINATIONS

These could aggravate several situations and require special investigation. Three such come quickly to mind:-

Compound angle gusts.

Excessive drag and speed loss in prolonged turns.

Effect of tail gust on inner wing in turn at bank limit.

It is not difficult to think of various aids to solution, but usually at the expense of undesirable complexity. Again further investigation is desirable.

## 5. DRAG IN TURBULENCE

Control difficulties arise with the larger gusts, drag effects are likely to be most serious with continuous turbulence at lower gust levels. There is one piece of clear cut evidence that this may be a problem from the cross channel flight of the Albatross, when Bryan Allen found he could only continue by flying higher in smoother air where the power demand was less. The cause of such drag increase has not been fully analysed but is thought to be associated with apparent mass effects and the repeated production of starting vortices as the wing lift fluctuates. A complicating influence lies in the likely spanwise fluctuations in lift associated with the smaller gusts in the spectrum.

This problem is amenable to theoretical analysis but full solutions will call for sophisticated methods and will depend on a good input model of the gust amplitude and spatial spectra. An important objective will be to establish the effect of height from the ground in the range of say 2 to 7 metres ( 5 to 20ft:).

## 6. CONCLUSIONS

1. Spiral divergence in turns with bank angles greater than about 16 deg: is possible.and could become difficult to control if accompanied by a tail gust on the inner wing. A clear visual indication of bank angle might suffice as a warning, but the possible need for a more positive preventive device should not be discounted.

2.Course control in smooth air should be adequate ,but doubt remains on the ability to deal with random side gusts. This is a complex problem requiring much further examination to avoid undue accident risk.

3. Simple theory indicates a possible problem with prolonged tail gusts causing excessive height loss and ensuing high ground impact velocities. HPAS are affected more suddenly than the higher speed sailplanes, but hang gliders are,theoretically, similarly affected to HPAS. This result is rather surprising as hang gliders appear to operate successfully, so the problem requires further investigation.

4. Experience with HPA indicates some drag increase when flying in turbulence. More work is needed to clarify this problem as, if significant, it could reduce eligibility for the sport and compound controllability problems.

## 7. RECOMMENDATIONS

1. Further work is needed in several areas where airworthiness is at issue. As sponsors of the HPAS competition, the Royal Aeronautical Society should maintain a watching brief on these matters until appropriate airworthiness standards are established by the C.A.A. et al. This action should proceed in advance of work by competition entrants to ensure timely advice as and when desirable.
2. Work in the following areas is very desirable as soon as practicable:-
Theoretical dynamic controllability studies with concurrent flight simulator work, covering disturbances in all degrees of freedom.
Associated specification of turbulence models in the near ground environment
Investigation of the effect of turbulence on drag.
3. As part of the above, liaison should be established with the Sailplane and Hang Gliding community.

## 8. REFERENCES


1. Kremer Human Powered Aircraft for Sport - Rules and Regulations. The Royal Aeronautical Society, Jan: 1996.

2. Man as an Aero Engine. D.R.Wilkie, Journal of the Royal Aerronautical Society, Aug: 1960.

3.The Human Power Plant. A.D.B.Evans, paper to H.P.A.G. Symposium, R.Ae.S, ca: 1980.

4. Estimation of Hours per Year when Mean Wind Speed exceeds Specified Thresholds. E.S.D.U. Data Sheet 88038.

5. Aerodynamics of Flight at Speeds under 5m/sec. Lissaman, Lex and Mcready, see R.Ae.S. library.

6. Preliminary Airworthiness Studies for Sporting Human Powered Aircraft. R.Blech, City University (unpublished).

7. Wind Speed Profiles over Terrain with Roughness Changes. E.S.D.U. Data Sheet 84011.


23rd January, 1996.

FIG. 1

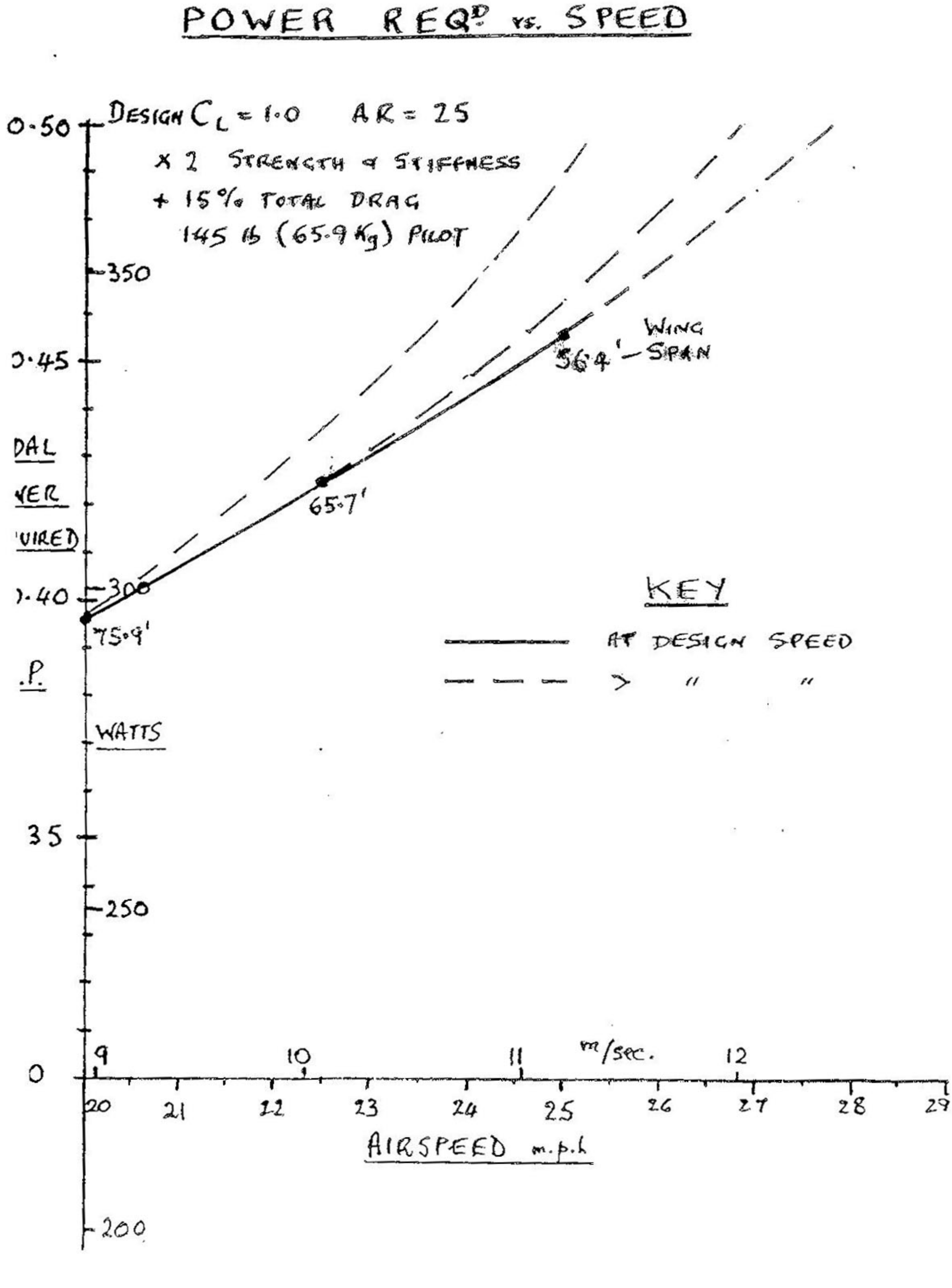

POWER REQ^D vs. SPEED
DESIGN C_L = 1.0 AR = 25
x 2 STRENGTH & STIFFNESS
+ 15% TOTAL DRAG
145 lb (65.9 Kg) PILOT
0.50
350
0.45
DAL
VER
UIRED
0.40
300
75.9'
P.
WATTS
35
250
0
200
65.7'
56.4'
WING SPAN
KEY
AT DESIGN SPEED
> " "
9
10
11
m/sec.
12
20
21
22
23
24
25
26
27
28
29
AIRSPEED m.p.h

FIG. 2

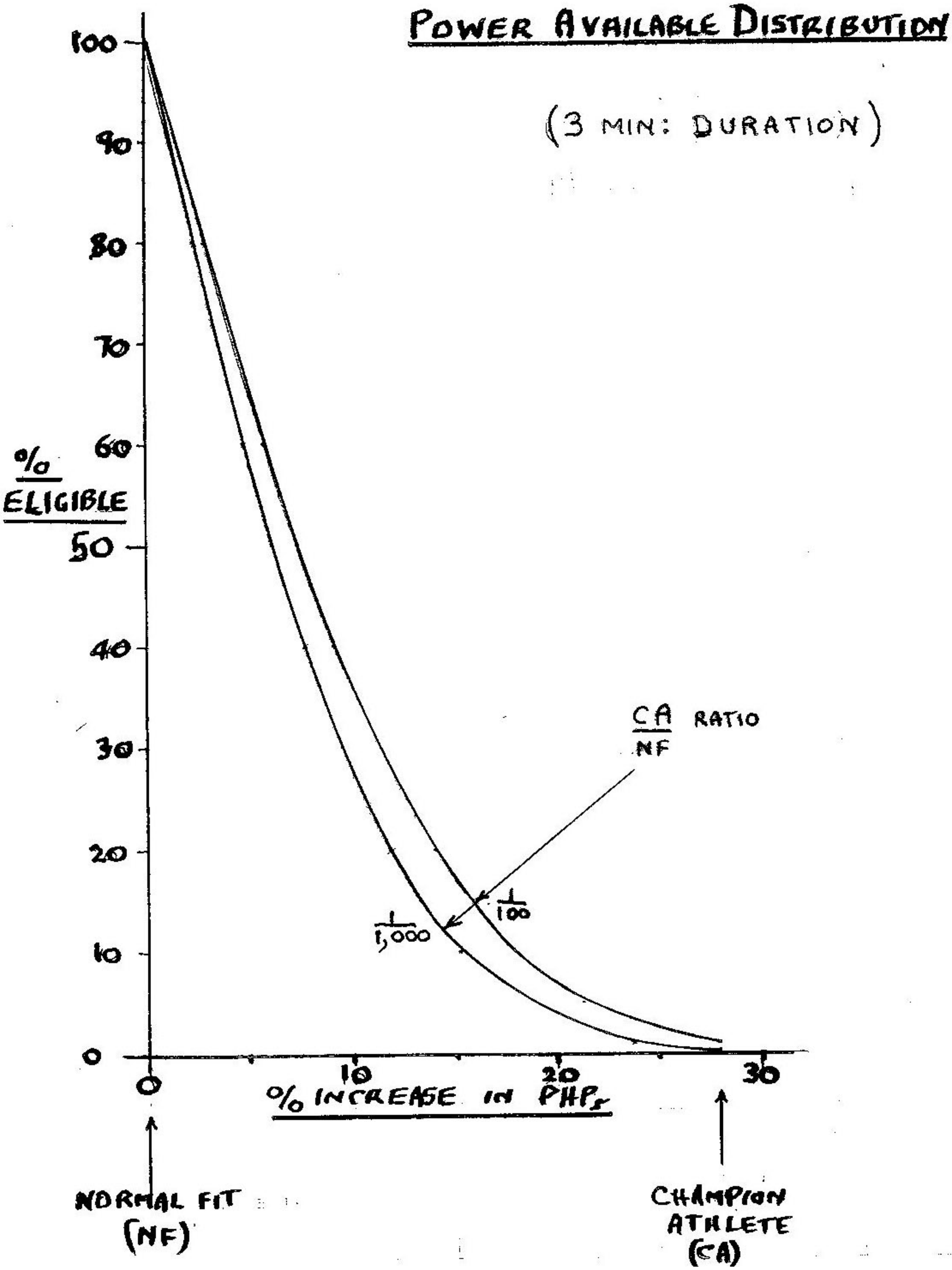
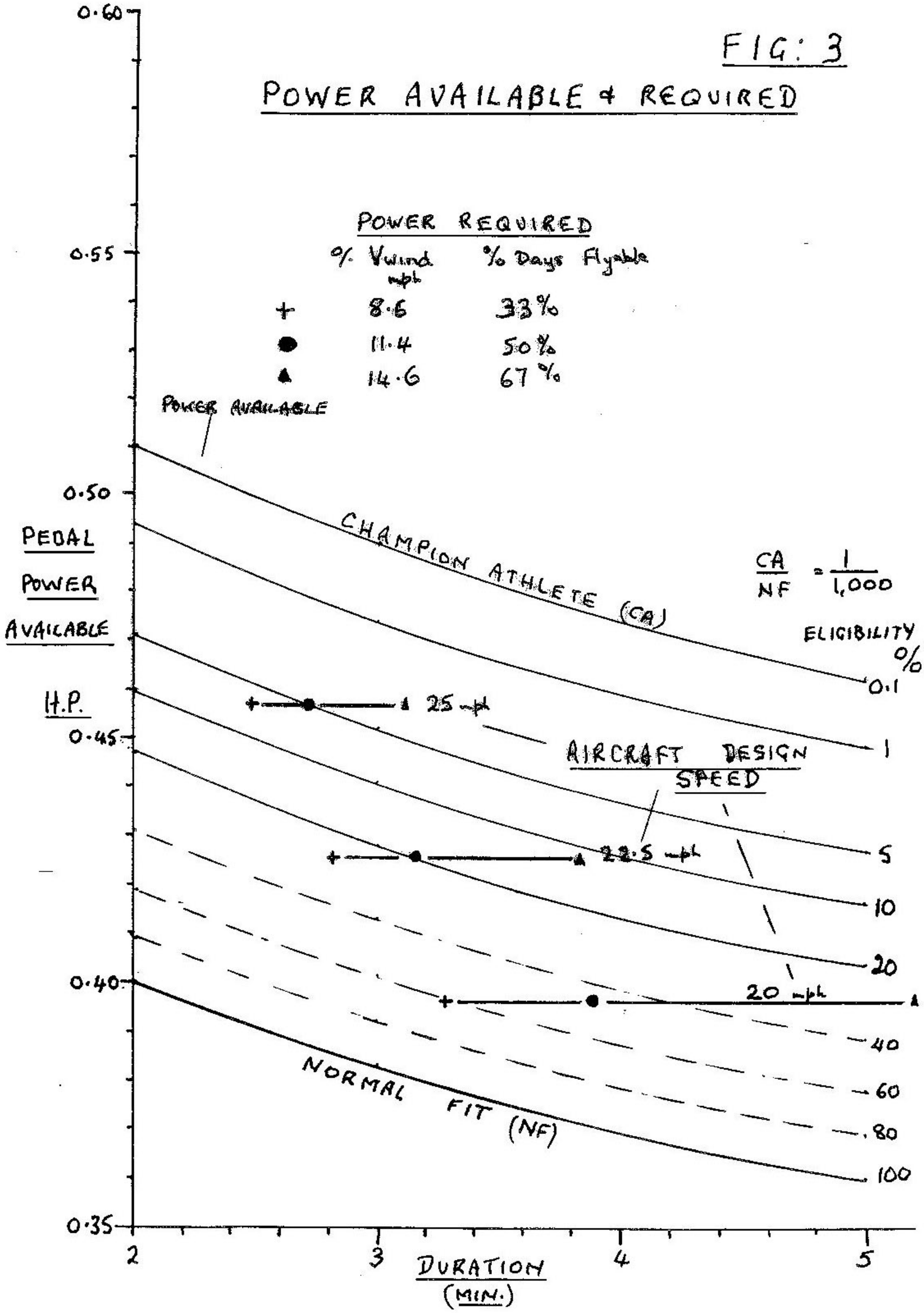

POWER AVAILABLE DISTRIBUTION
(3 MIN: DURATION)
%
ELIGIBLE
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
% INCREASE IN PHPs
CA/NF RATIO
1/100
1/1,000
NORMAL FIT
(NF)
CHAMPION
ATHLETE
(CA)

FIG: 3



POWER AVAILABLE & REQUIRED
POWER REQUIRED
% Vwind mph
% Days Flyable
+ 8.6 33%
● 11.4 50%
▲ 14.6 67%
POWER AVAILABLE
CHAMPION ATHLETE (CA)
CA/NF = 1/1,000
ELIGIBILITY %
0.1
1
5
10
20
40
60
80
100
25 mph
22.5 mph
20 mph
AIRCRAFT DESIGN SPEED
NORMAL FIT (NF)
PEDAL POWER AVAILABLE
H.P.
0.60
0.55
0.50
0.45
0.40
0.35
2
3
4
5
DURATION (MIN.)

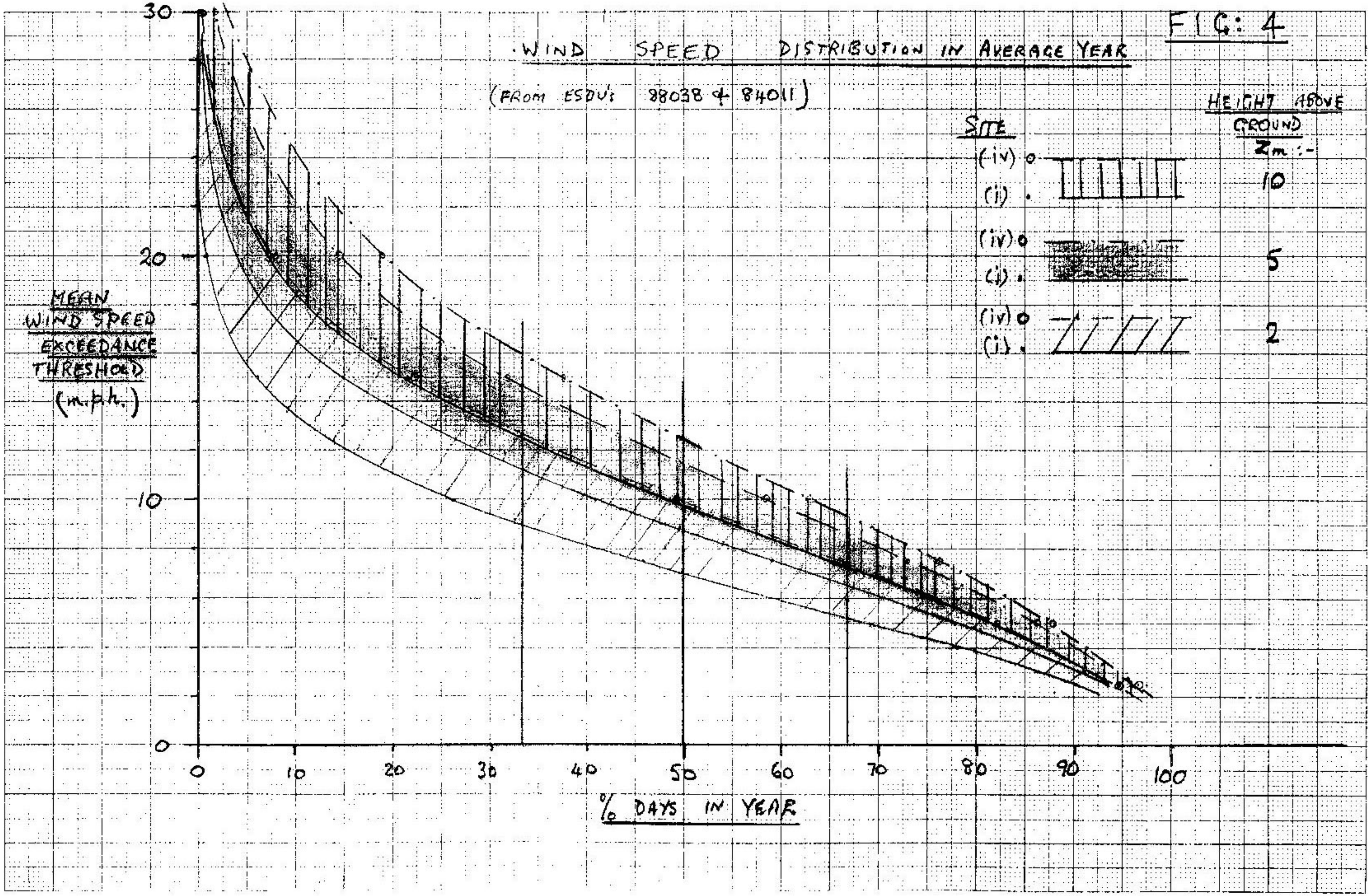
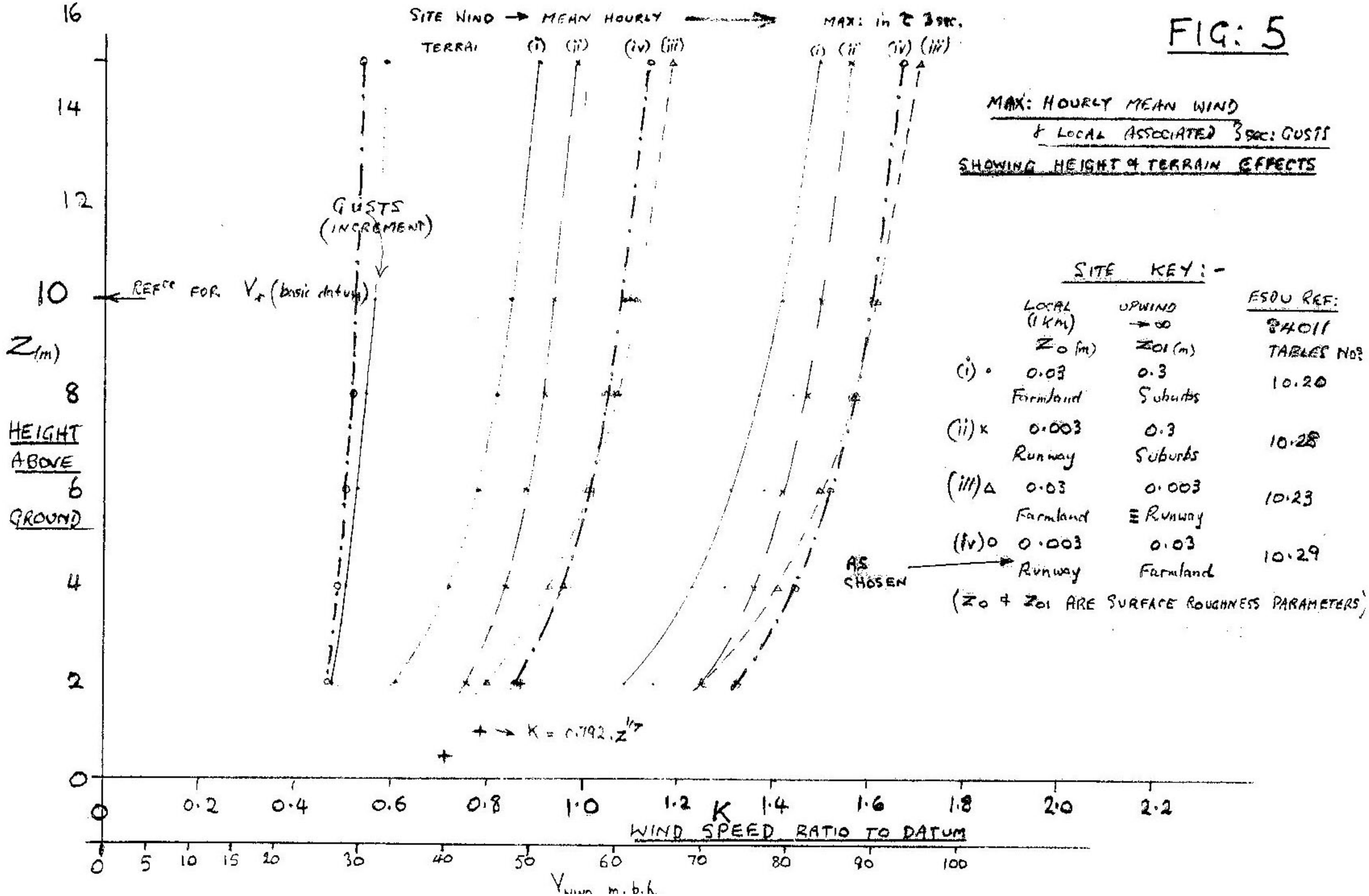


FIG: 4
WIND SPEED DISTRIBUTION IN AVERAGE YEAR
(FROM ESDU's 88038 & 84011)
SITE
HEIGHT ABOVE GROUND
Zm :-
(iv) o
(i) •
10
(iv) o
(i) •
5
(iv) o
(i) •
2
MEAN WIND SPEED EXCEEDANCE THRESHOLD (m.p.h.)
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
% DAYS IN YEAR

FIG: 5



SITE WIND → MEAN HOURLY → MAX: in 3 sec.
TERRAI (i) (ii) (iv) (iii) (i) (ii) (iv) (iii)
MAX: HOURLY MEAN WIND
& LOCAL ASSOCIATED 3 sec: GUSTS
SHOWING HEIGHT & TERRAIN EFFECTS
GUSTS (INCREMENT)
REFce FOR Vz (basic datum)
Z (m)
HEIGHT ABOVE GROUND
16
14
12
10
8
6
4
2
0
SITE KEY:-
LOCAL (1 km) Zo (m)
UPWIND → ∞ Zo1 (m)
ESDU REF: 84011 TABLES No.
(i) • 0.03 Farmland 0.3 Suburbs 10.20
(ii) x 0.003 Runway 0.3 Suburbs 10.28
(iii) Δ 0.03 Farmland 0.003 ≡ Runway 10.23
(iv) o 0.003 Runway 0.03 Farmland 10.29
AS CHOSEN
(Zo & Zo1 ARE SURFACE ROUGHNESS PARAMETERS)
+ → K = 0.792 . Z^1/7
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2
K
WIND SPEED RATIO TO DATUM
0 5 10 15 20 30 40 50 60 70 80 90 100
V m.p.h.

# COMPETITION PERFORMANCE

FIG: 6

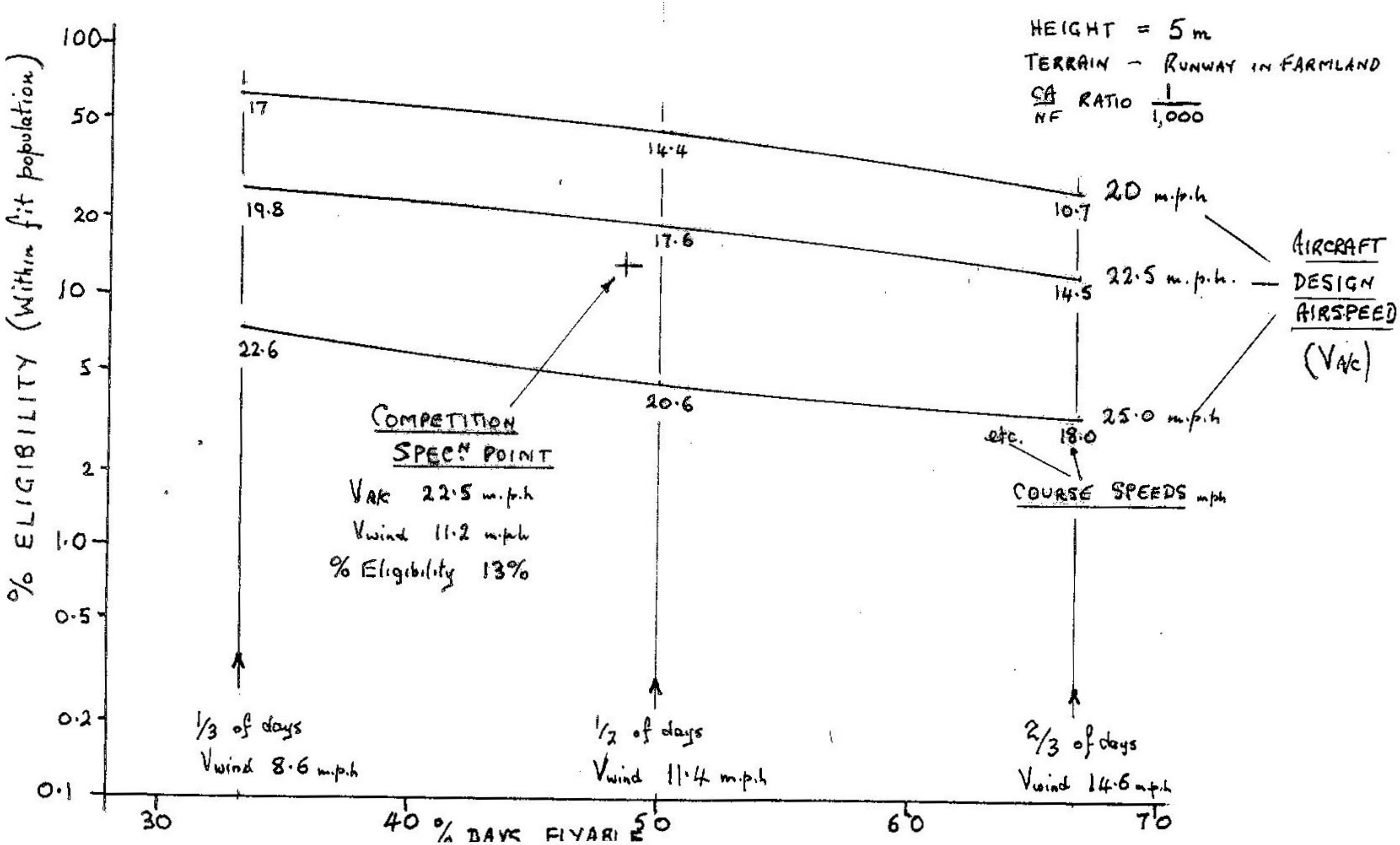
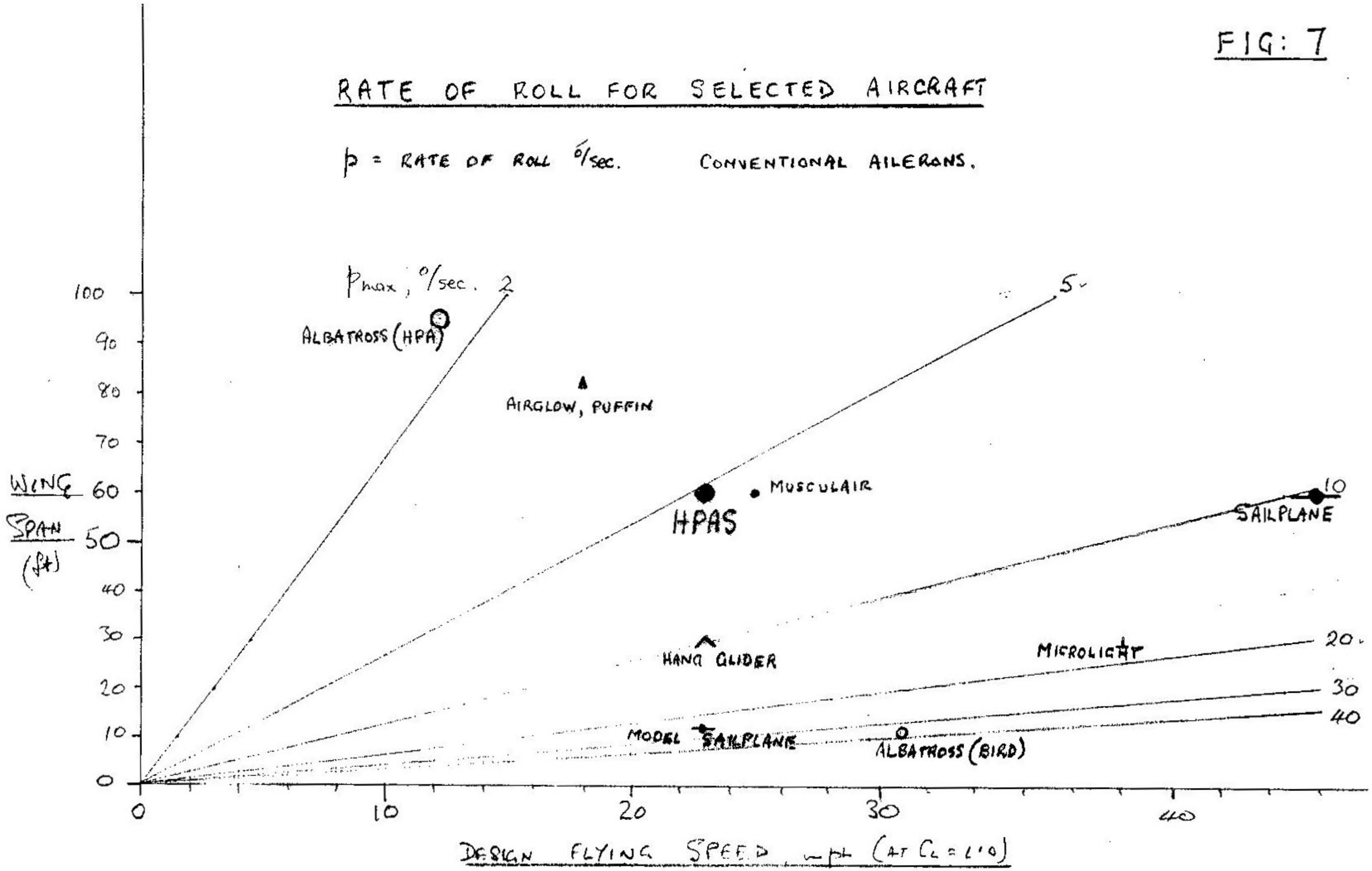


FIG: 7



RATE OF ROLL FOR SELECTED AIRCRAFT
p = RATE OF ROLL °/sec.
CONVENTIONAL AILERONS.
p max, °/sec.
2
5
10
20
30
40
ALBATROSS (HPA)
AIRGLOW, PUFFIN
HPAS
MUSCULAIR
SAILPLANE
HANG GLIDER
MICROLIGHT
MODEL SAILPLANE
ALBATROSS (BIRD)
WING SPAN (ft)
0
10
20
30
40
50
60
70
80
90
100
DESIGN FLYING SPEED mph (AT CL = 1·0)

FIG: 8

CRITICAL BANK ANGLE SEQUENCE

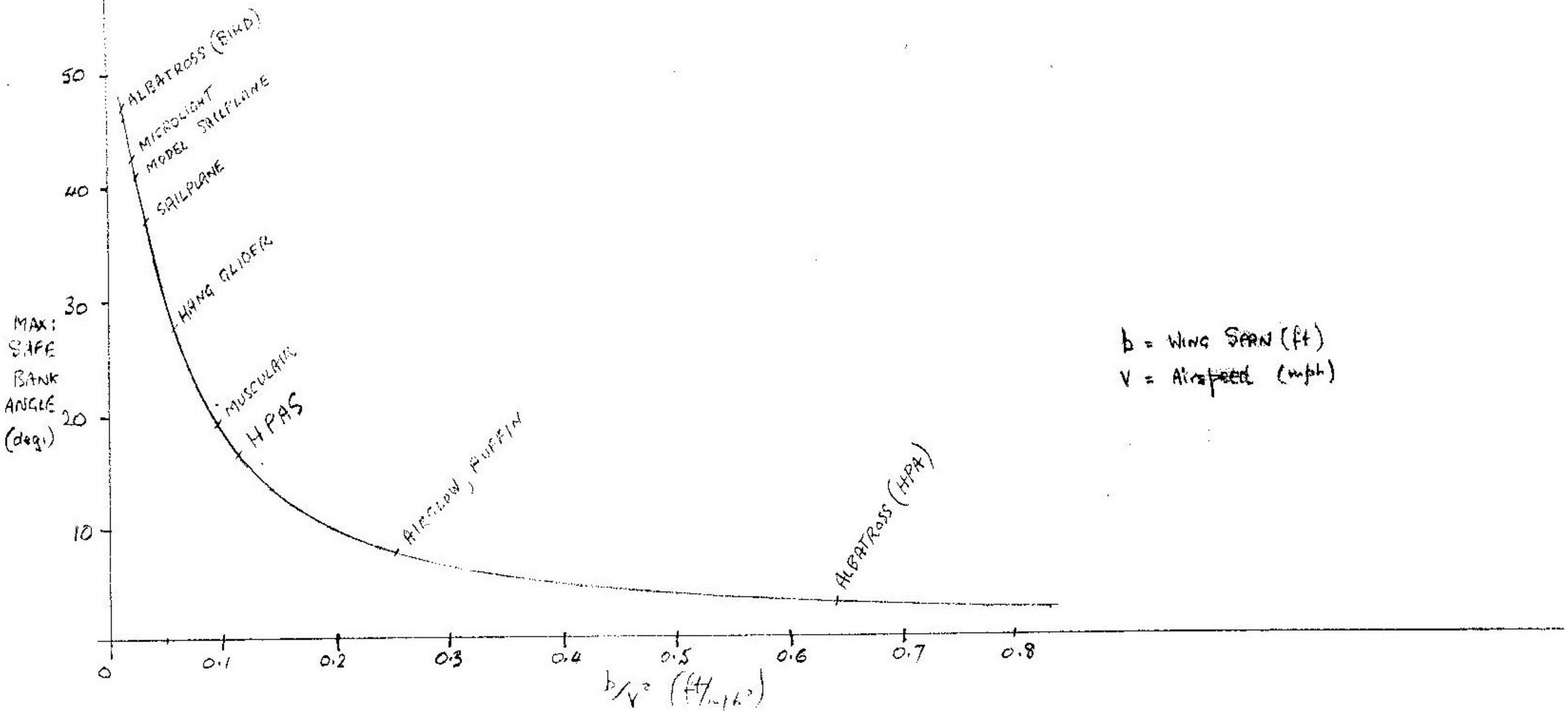
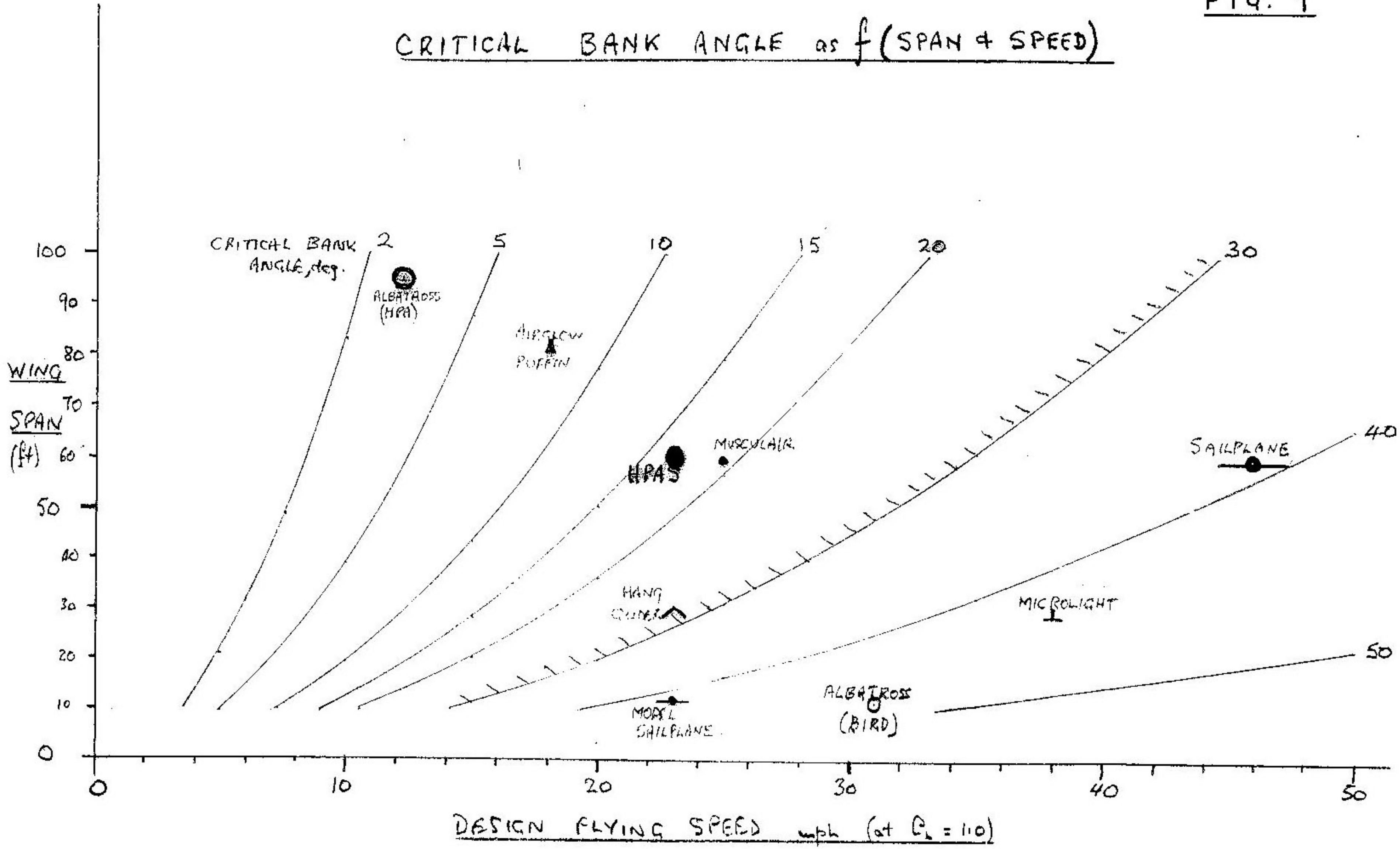


FIG: 9



CRITICAL BANK ANGLE as f (SPAN & SPEED)
CRITICAL BANK ANGLE, deg.
2
5
10
15
20
30
40
50
ALBATROSS (HPA)
AIRGLOW PUFFIN
HPAS
MUSCULAIR
HANG GLIDER
SAILPLANE
MICROLIGHT
MODEL SAILPLANE
ALBATROSS (BIRD)
WING SPAN (ft)
0
10
20
30
40
50
60
70
80
90
100
DESIGN FLYING SPEED mph (at $C_L$ = 1.0)

FIG: 10

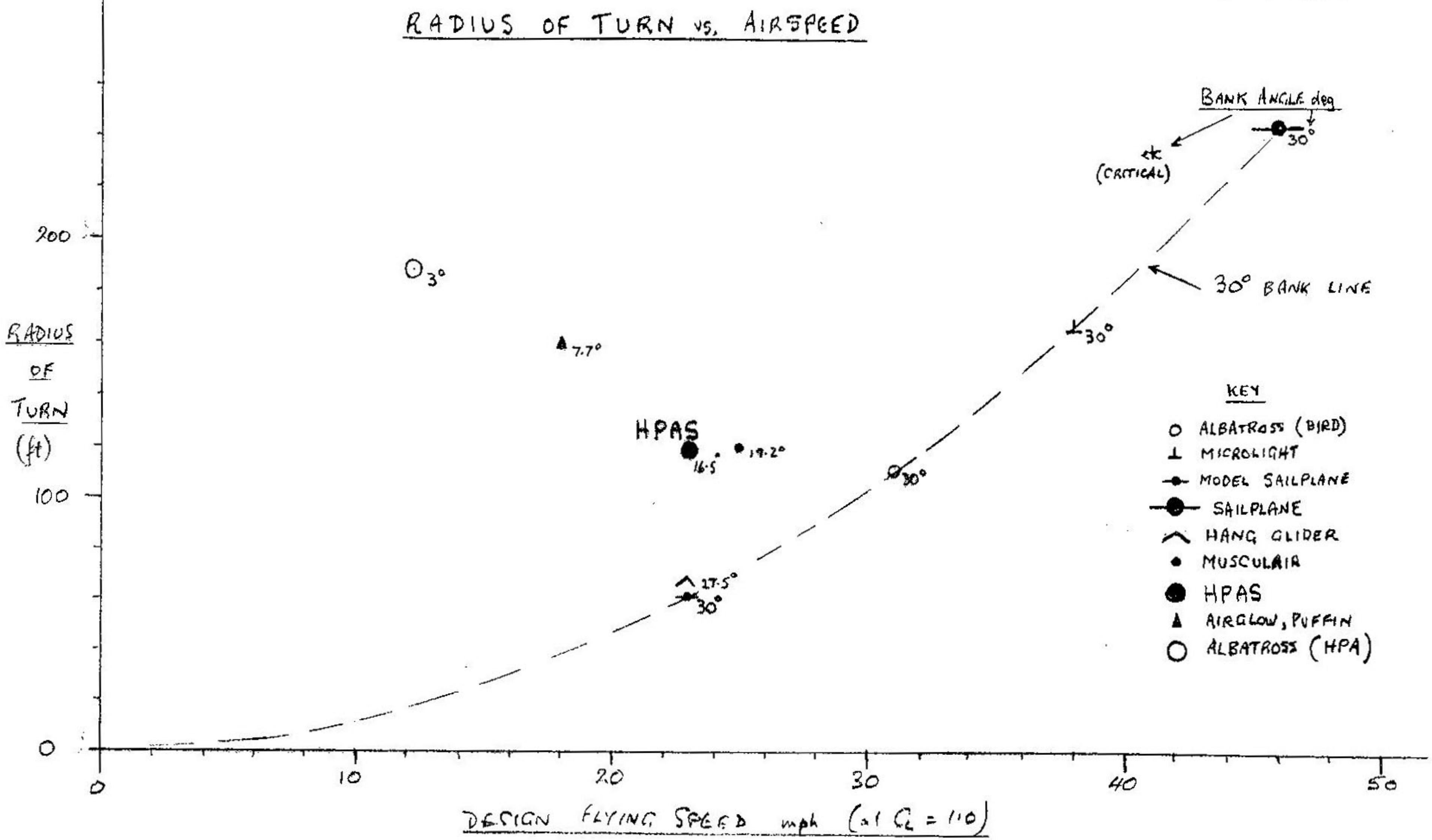
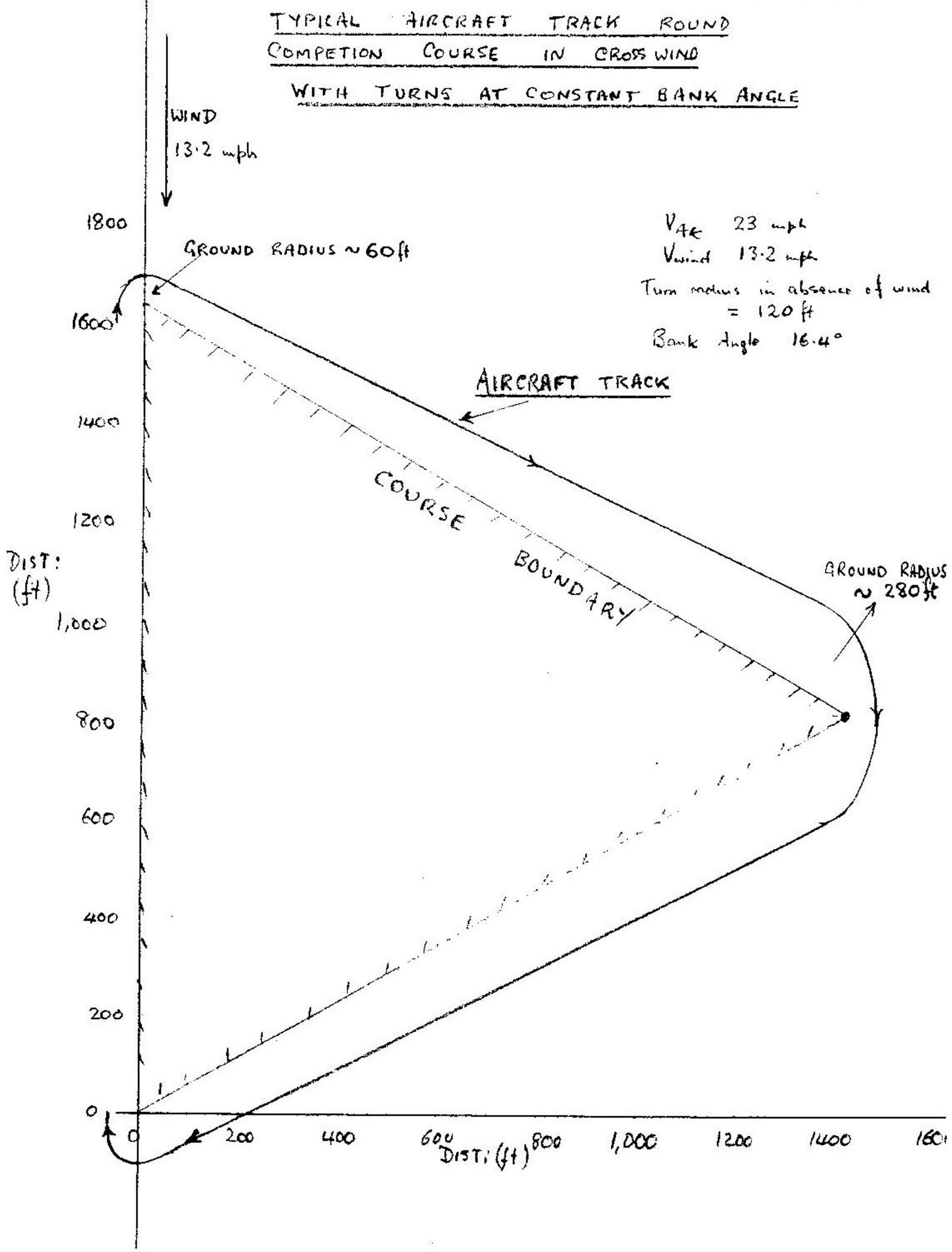

RADIUS OF TURN vs. AIRSPEED
RADIUS OF TURN (ft)
200
100
0
DESIGN FLYING SPEED mph (at CL = 1.0)
0
10
20
30
40
50
BANK ANGLE deg
(CRITICAL)
30°
30° BANK LINE
3°
7.7°
HPAS
16.5
19.2°
27.5°
KEY
ALBATROSS (BIRD)
MICROLIGHT
MODEL SAILPLANE
SAILPLANE
HANG GLIDER
MUSCULAIR
HPAS
AIRGLOW, PUFFIN
ALBATROSS (HPA)

FIG: 11



TYPICAL AIRCRAFT TRACK ROUND
COMPETION COURSE IN CROSS WIND
WITH TURNS AT CONSTANT BANK ANGLE
WIND
13·2 mph
$V_{AC}$ 23 mph
$V_{wind}$ 13·2 mph
Turn radius in absence of wind
= 120 ft
Bank Angle 16·4°
GROUND RADIUS ~ 60ft
AIRCRAFT TRACK
COURSE
BOUNDARY
GROUND RADIUS
~ 280ft
DIST:
(ft)
1800
1600
1400
1200
1,000
800
600
400
200
0
0
200
400
600
800
1,000
1200
1400
DIST: (ft)

FIG: 12

# OPTIMUM BANK SEQUENCE IN 'S' TURNS

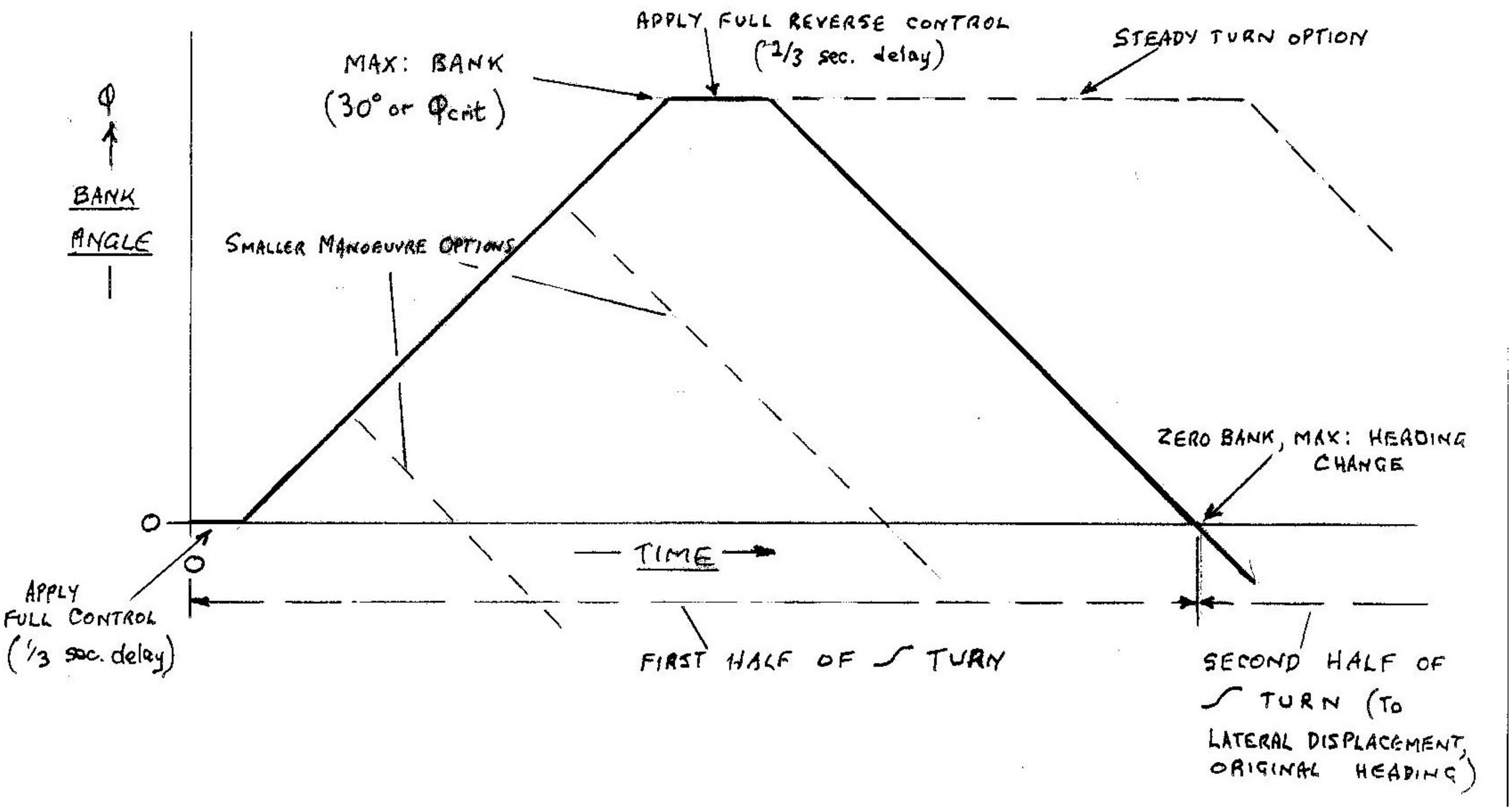


FIG: 13

## COURSE CHANGE vs PEAK BANK

(PULSE AILERON USE)

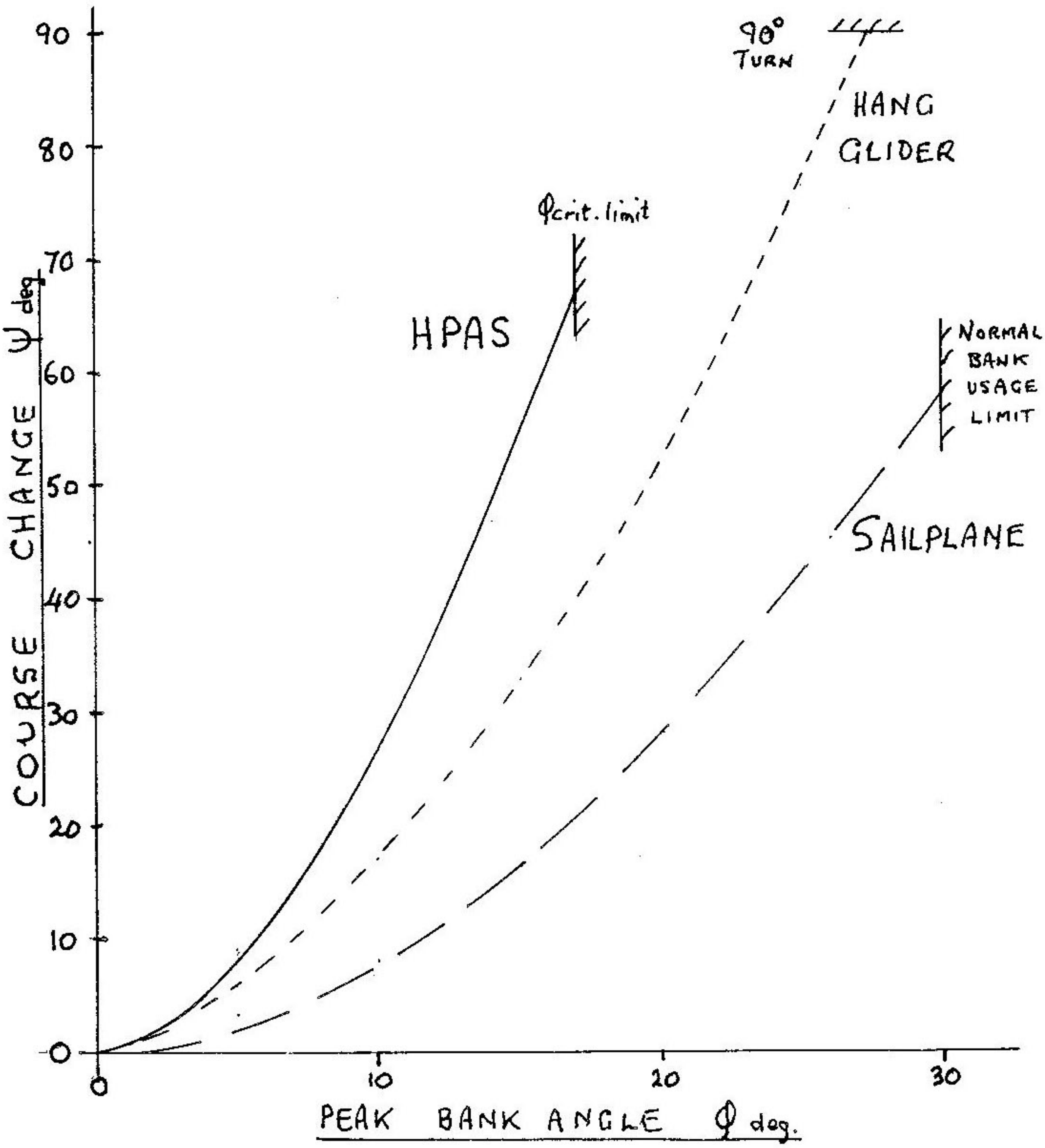


FIG: 14

# COURSE CHANGE vs. TIME

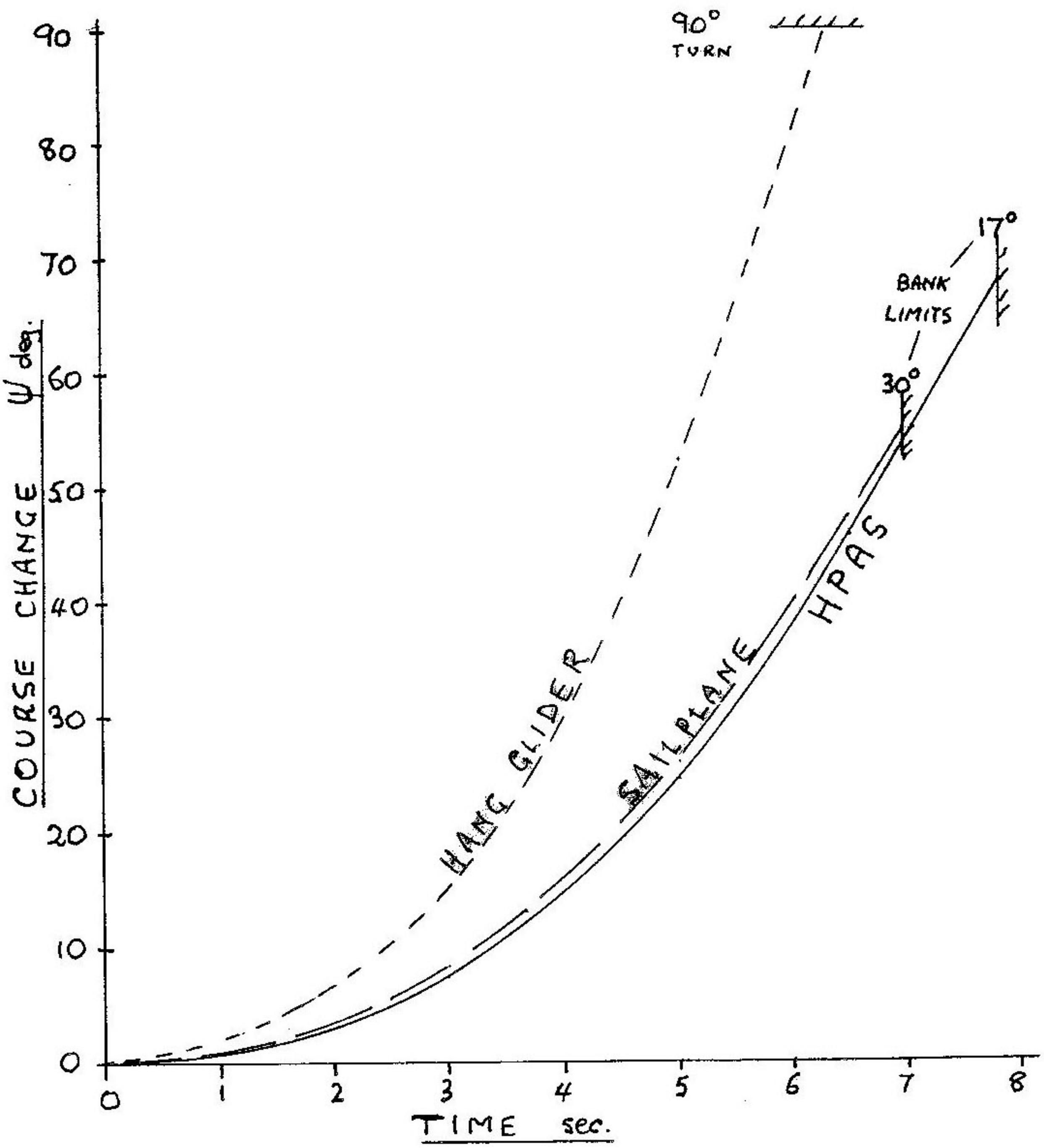
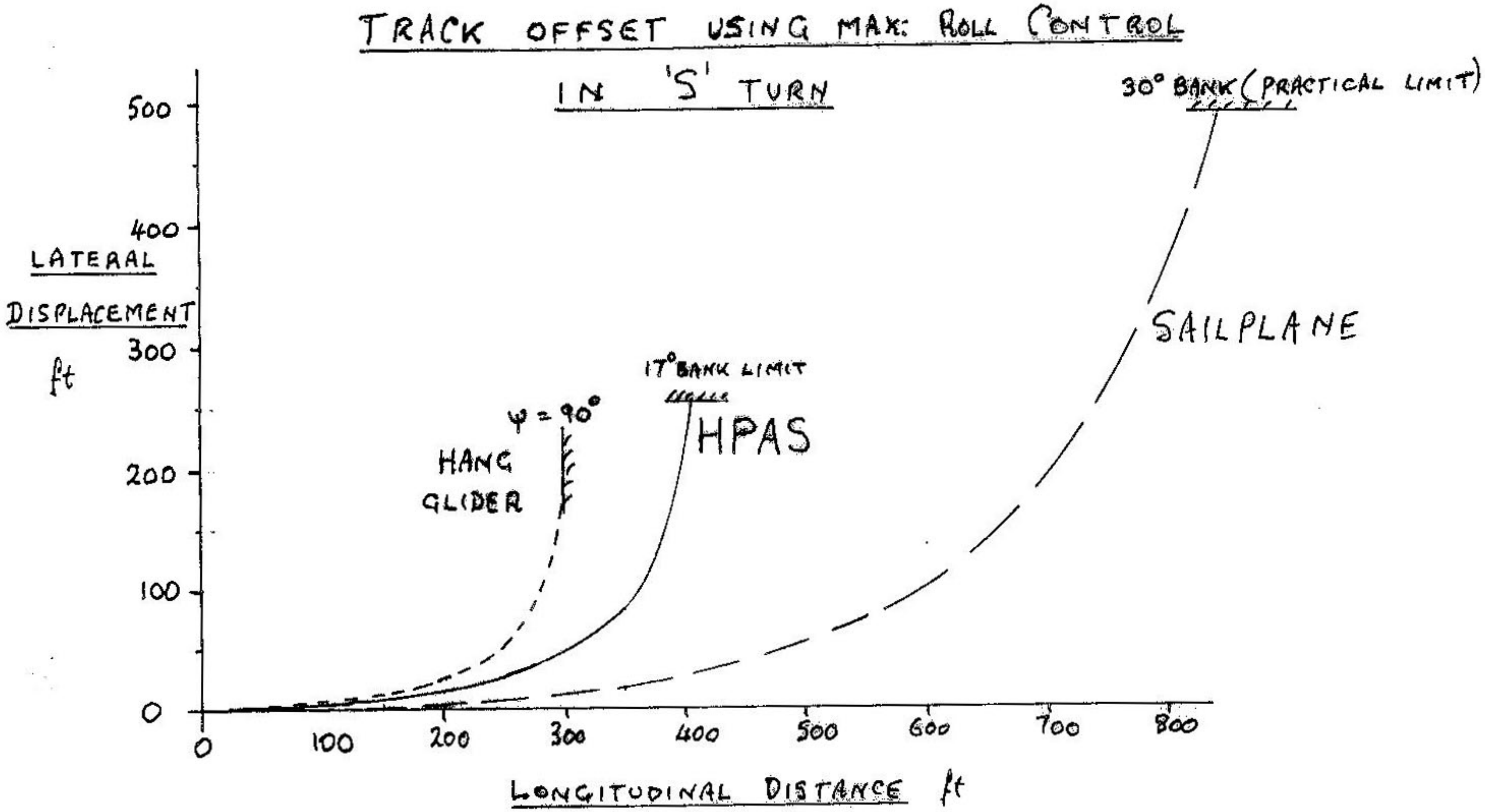
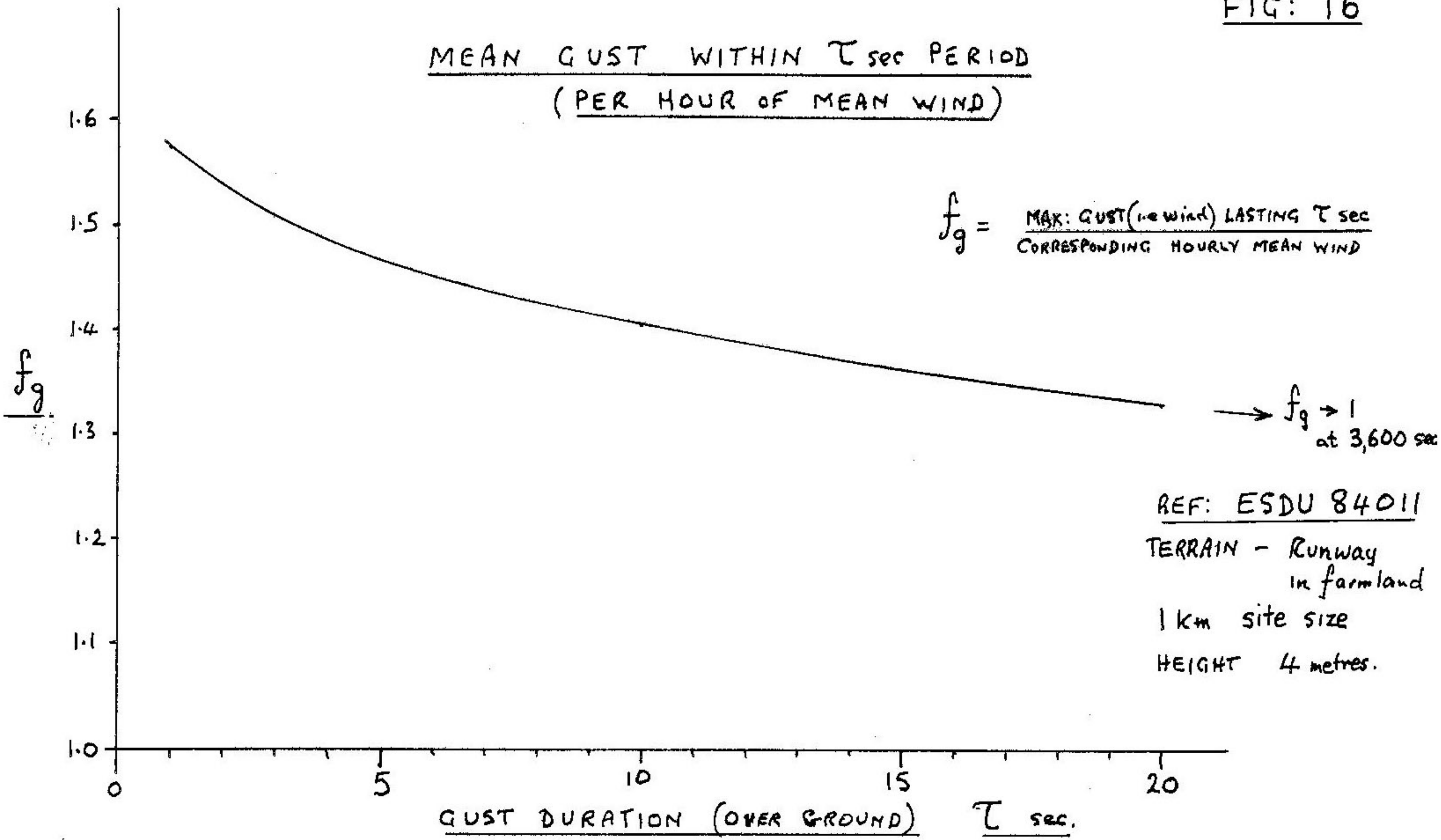


FIG: 15



TRACK OFFSET USING MAX: ROLL CONTROL
IN 'S' TURN
LATERAL DISPLACEMENT ft
500
400
300
200
100
0
LONGITUDINAL DISTANCE ft
0
100
200
300
400
500
600
700
800
30° BANK (PRACTICAL LIMIT)
SAILPLANE
17° BANK LIMIT
HPAS
ψ = 90°
HANG GLIDER

FIG: 16



MEAN GUST WITHIN τ sec PERIOD
(PER HOUR OF MEAN WIND)
f_g = MAX: GUST (i.e wind) LASTING τ sec / CORRESPONDING HOURLY MEAN WIND
f_g
1·6
1·5
1·4
1·3
1·2
1·1
1·0
0
5
10
15
20
→ f_g → 1 at 3,600 sec
REF: ESDU 84011
TERRAIN - Runway in farmland
1 km site size
HEIGHT 4 metres.
GUST DURATION (OVER GROUND) τ sec.

# EFFECT OF WORST TAIL GUST