A SIGNIFICANT INCREASE IN LIFT TO DRAG RATIO OF AIRFOILS AT LOW REYNOLDS NUMBER THROUGH THE USE OF MULTIPLE TRIPPERS AND LOW DRAG LAMINAR FLOW

A TRIBUTE TO THE WORK OF DR. WERNER PFENNINGER

By BRUCE H. CARMICHAEL

"Mysterious even on the brightest day
To be unveiled by duress Nature doth refuse
What she reveals not to thy intellect
Thou will not force from her with levers and with screws."

Goethe

ABSTRACT

Low turbulence experimental data obtained in 1956 but not widely published heretofore, provides promise of considerable A-2 performance improvement. In restricting both thickness and camber below traditional values and placing a trip step just sufficiently forward to match the design Reynolds number, Dr. Werner Pfenninger was able to keep the profile drag only 55% in excess of the drag of two sides of a laminar plate. In spite of a design lift coefficient of only 0.77, both section L/D and section $L^{3/2}/D$ are quite superior to any other data found to date.

Application of this data to an A-2 performance study reveals that the minimum allowable wing loading of 0.247 #/sq.ft. and optimum aspect ratio of 20 results in a chord Reynolds number of 35,000, an L/D of 22.4, and a minimum sinking speed of 0.74 ft/sec. In still air from a 164 ft. launch, the time to descend would be 3.7 minutes. It will undoubtedly take time to capitalize on this in the real world of contest flying but the direction for experimentation seems clear.

INTRODUCTION

The realization that a large gulf exists between the peformance of model and full scale aircraft, that full scale airfoils are unsuitable for models, and that the ambience turbulence level has a large effect on the critical Reynolds number of airfoils, is generally attributed to the classical work of Schmitz (Ref. 1). It is not generally realized that another quiet genius was at work on the same problem even earlier. Dr. Werner Pfenninger explored thin laminar airfoils at moderate lift coefficient down to Reynolds numbers as low as 60,000. This low turbulence, low Reynolds number work (started in 1940) was buried in a huge report in which the principle emphasis was on fully laminar wing sections employing boundary layer suction at somewhat higher Reynolds numbers. This work was translated and published as NACA TM-1181 (Ref. 2) in the mid 40's and should be required reading for every working aerodynamicist once a year.

After moving from Zurich Switzerland to the USA at the invitation of Jack Northrop, Dr. Pfenninger extended his low drag work to very high Reynolds numbers and high subsonic Mach numbers. In 1956 he once more explored the low RN regime with a non suction airfoil (Ref. 3). This Northrop B.L.C. report was done as a portion of a Wright Field contract and was not widely circulated. It is the keystone in my search for the window in the performance barrier.

THE PFENNINGER PF 4.2 36-4.8 30 AIRFOIL

I have followed the designation method of C.W. Bogart (Ref. 4) in defining the section. It has 4.2% camber at 36% chord and 4.8% thickness at 30% chord. The leading edge radius is about 0.35% of the chord. The form can be seen in Table 1 which also provides coordinates.

Table 1 The remarkable Pfenninger airfoil

X/C	Y/C UPPER	Y/C LOWER
0.00	0.00	0.00
0.01	0.01	0.0012
0.025	0.018	0.0028
0.05	0.028	0.0042
0.075	0.0345	0.0052
0.10	0.040	0.0070
0.15	0.049	0.0096
0.20	0.056	0.012
0.30	0.0641	0.016
0.40	0.0655	0.016
0.50	0.0618	0.0177
0.60	0.055	0.016
0.70	0.045	0.013
0.80	0.0318	0.009
0.90	0.0162	[illegible]
1.00	0.00	0.00

SPANWISE RUNNING TRIPP TAPES

EACH 0.012 inch high 3.5% chord wide

CHORDWISE LOCATIONS

(A) 3 TRIPPS
.48→.515, .62→.655, .735→.77c

(B) 4 TRIPPS
.41→.455, .515→.55, .64→.675, .725→.76c

(C) 5 TRIPPS
.268→.303, .40→.435, .52→.555, .635→.67c
.76→.795c

Note that these were scaled from a large drawing. Spline techniques should be used in constructing your templates. The bottom surface in particular should be kept very smooth and slick since it will be completely laminar at design lift coefficient. The upper surface should also be accurately constructed even though it will have several trip strips installed.

THE EXPERIMENT OF REFERENCE 3

A two-dimensional model of 5 inch chord and 8 inch span was tested in an 8 inch diameter flow tube. The very low turbulence level of the facility was assured by many fine damping screens at the entrance nozzle. A rubber pinch valve downstream of the test section created sonic flow and prevented upstream travel of any noise or disturbances from the war-surplus supercharger that powered the tunnel. The drag values were computed by the momentum loss method from velocities measued with a fine total head survey probe in the wake at the center of the span. The lift was obtained by integration of the pressure distribution which was measured with a tiny static probe. Transition and separation information were obtained with a probe and stethescope. It was found necessary to install 0.012 inch thick 0.18 inch wide strips of masking tape at various chordwise stations on the upper surface. The free vortex layers and highly unstable boundary layer velocity profiles with inflexion points downstream of

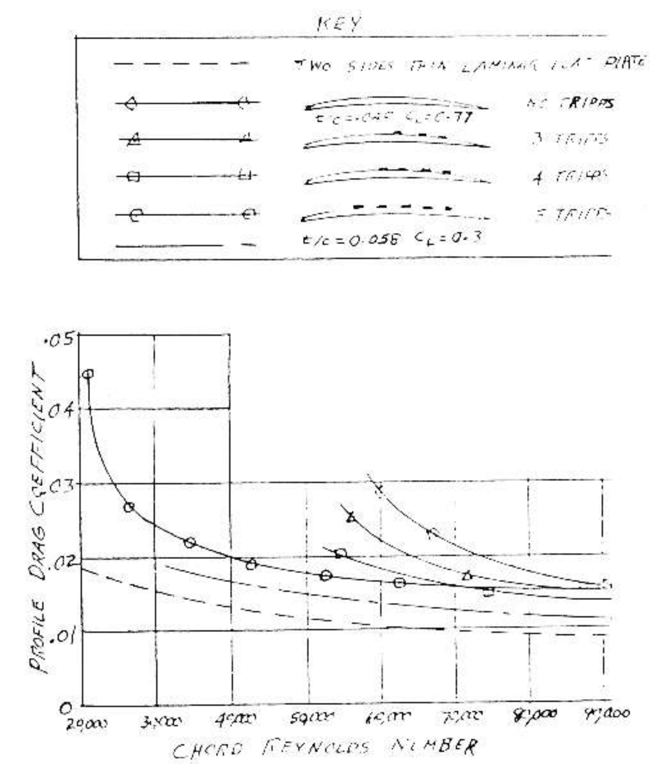

Fig. 1 Two dimensional profile drag coefficient for Pfenninger 4.2-36, 4.8-30 Airfoil with various upper surface trippers

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each strip kept the f..w attached. The drag could be reduced in this manner at chord Reynolds numbers as high as 100,000. In view of this result one should expect to require trip devices of thicker, more highly cambered sections with higher design lift coefficients at Reynolds numbers equal to or less than 100,000, if one is to obtain best performance.

Most of the measurements were conducted at α = 4° close to the upper limit of the favorable lift range. The lift coefficient was 0.77 for reattached turbulent flow. Blockage corrections were applied to the apparent lift coefficient obtained from integration of the measured pressure distributions. The Reynolds number was varied between 20,000 and 92,000.

THE EXPERIMENTAL RESULTS

The variation of two-dimensional profile drag with wing chord Reynolds number is shown in Figure 1. The approach of the remarkably low drag to twice the laminar flat plate value is evident as well as the trip requirement to retain this to ever lower Reynolds numbers. Results from his classical Zurich work are included for a 5.8% thick section at C_L of 0.3 and show an even closer approach to the laminar line.

The use of a probe attached to a simple doctors' stethescope revealed that laminar flow extended to the trailing edge on the lower surface at design C_L for all Reynolds numbers tested. It also revealed laminar separation without reattachment on the upper surface in the absence of sufficient tripping. This observation coincides with the Reynolds numbers where the profile drag is seen to rise steeply from the minimum drag envelope in Figure 1. With five trip strips spread out from 0.268C to 0.80C the minimum drag envelope was achieved down to RN = 40,000. At a Reynolds number of 20,000 this trip configuration has failed to prevent a doubling of the profile drag expected from an extrapolation of the minumum drag envelope. It should be noted that above RN = 100,000 the trip is not required and will lead to higher drag than results for the clean airfoil.

At each value of Reynolds number, there exists a location of the trailing edge of the most forward trip strip for which transition occurs just in time to insure flow reattachment. Tripping the upper surface laminar flow further forward results in additional drag and is unnecessary. The trip locations are summarized in Figure 2 for the 4.8% thick airfoil and extended to higher Reynolds number with results of aft facing steps in a 6% thick airfoil from Reference 2. Extrapolation of this curve to the leading edge would indicate that at least this type of tripper has lost its effectiveness to keep flow attached when the Reynolds number falls to 16,000.

Fig. 2 Location of T.E. of first tripper as function of Chord R.N.

If we assume the blockage corrections are perfect and that the section C_L is indeed 0.77 for all Reynolds numbers of this test, the L/D values for the two dimensional airfoil can be obtained by dividing 0.77 by the envelope drag values. Likewise the sinking speed parameter can be obtained by dividing $(0.77)^{1.5}$ or the constant 0.675 by the envelope drag values to provide $L^{3/2}/D$.

COMPARISON WITH OTHER AIRFOIL RESULTS

One would expect a moderate camber airfoil like this to perhaps have an edge in L/D but one would expect that it might not have a superior sink parameter. Improved airfoils of greater camber incorporating trippers, in spite of moderately higher drag, should produce an increased design lift coefficient which when raised to the 1.5 power, should provide superior sink parameters.

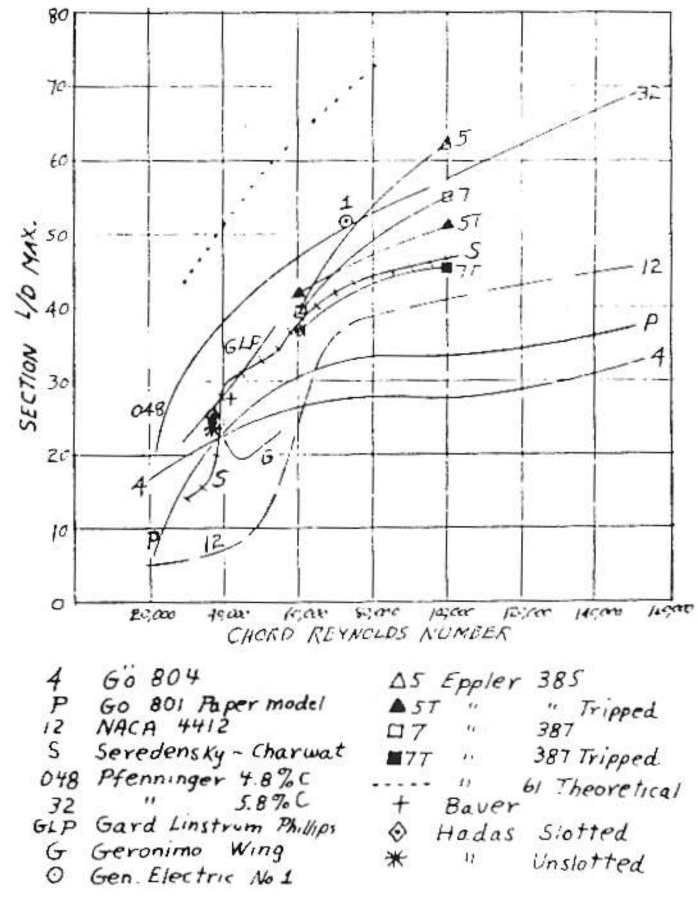

Fig. 3 Two dimensional maximum glide ratios

At the time I began this study, I sent letters frantically in all directions in an attempt to establish the state of the art. I was amazed at the instant response and whole hearted cooperation of the many talented members of the scientifically and technically inclined model building community. I am forced to attend my mailbox with a wheelbarrow these days.

Thank you, Bauer, Brown, Dodds, Eggleston, Eppler, Hodges, Isaacson, Jex, Karem, Lissamen, Marsden, Miley, Miller, Phillips, Pressnell, Pfenninger, Sidderman, Smith, Wagner, van Ingen, Volkers, Wortmann, and Zaic. The NFFS Yearly Reports and the Zaic Yearbooks are particularly rich gold mines of fine technical contributions.

The Pfenninger section with trips is seen to be superior in L/D to all other data over the complete Reynolds number range from 20,000 to 75,000. (Figure 3). The Eppler 385 appears at RN 100,000 to be a bit better than the Pfenninger section while the Eppler 387 is just slightly inferior (Ref. 11). The 387 is somewhat more inferior to the Pfenninger at 60,000 RN. A slightly lower L/D was obtained on the 387 at 60,000 with trip. At 100,000 use of the trip resulted in significantly lower L/D. This was also true for the 385 at 100,000 RN, while the 385 improved with trip at 60,000 RN.

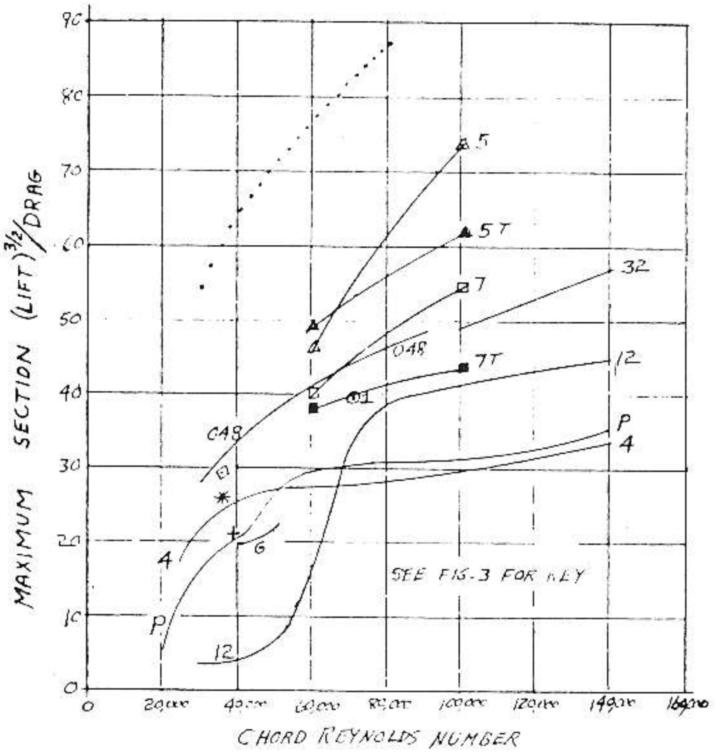

Fig. 4 Two dimensional sinking speed parameter

The reliable old NACA 4412 (Ref. 5) is seen to be a good section above 75,000 but miserable in the A-2 range. The data of Kraemer (Ref. 7) reveals little choice between the Go804 and the practical construction Go801 in the A-2 range although the 801 is significantly better at RN greater than 50,000. The GLP section tested by Phillips in England is good but falls well below the Pfenninger section. Glide tests on a slotted or two element wing (Ref. 9) fall in with the GLP data. The performance decreased slightly when the slot was closed. Wind tunnel tests of a half wing of practical construction from the Geronimo (Reference 10) have shown L/D values lower than the Go 804.

The Blade profile No. 1 of Reference 12 looks very much like the Pfenninger section. Its measured L/D fell right on the Pfenninger value at an effective RN of 71,000.

The tests of Andy Charwat (Ref. 13) upon the bird-like airfoil of Vladimir Seredensky produced an interesting curve of L/D vs. RN. There is a rapid rise in value at a critical value of about 38,000 followed by a slight level off and a second steep rise between 50,000 and 70,000. Although inferior to the Pfenninger section it is much thicker and still is about as good as any other thick section for which test data is available betwen RN of 40,000 and 60,000.

It will now be most important to get good low turbulence tunnel data on the thin Eppler 61 for which significantly higher performance is predicted than has been obtained on the Pfenninger. It should be noted that the test results (Ref. 11) on the Eppler 385 and 387 came close to Dr. Eppler's theoretical estimates. Of course the range of RN between 30,000 and 60,000 is much more difficult to handle theoretically, but the Eppler 61 as well as the 58, 59, and 62 are thin sections with a promising appearance to them.

The sinking speed parameter $L^{3/2}/D$ vs. RN is shown in Figure 4. The Go804 is superior to the 801 in the A-2 range. The Geronimo data is inferior to both as is the NACA 4412. Only the slotted wing approaches the Pfenninger values. The Geronimo is slightly inferior to the 804.

At 60,000 RN the Eppler 387 falls right on the Pfenninger curve and the Eppler 385 slightly above (Ref. 11). At 71,000 effective RN the blade section 1 of Reference 12 is slightly inferior to the Pfenninger curve. At 100,000 RN the Eppler 385 is greatly superior to the Pfenninger, the E 387 is somewhat superior in the clean condition and somewhat inferior when tripped (Ref. 11).

It appears that the Pfenninger 4.8% thick section is superior to everything found to date in both L/D and $L^{3/2}/D$ at Reynolds numbers less than 60,000. It is possible that higher low Reynolds number values may be achieved with a bit more camber and optimum trips. It is again imperative that the Eppler 61 be tested at RN down to 30,000 in a low turbulence wind tunnel.

The characteristics of the sections discussed above and their test facilities are summarized in Table 2.

Table 2

REF.	EXPERIMENTER	TEST FACILITY	TURB. LEVEL
2	Pfenninger	Zurich ETH	mod. low
3	Pfenninger	Flow Tube	very low
5	Lneenicka	?	?
7	Kraemer	Gottingen	0.1%
8	Phillips	Cranfield	low
9	Hadas	Free Flight	vanishingly small
10	Hendricks	Delft U.	very low
11	Volkers	Delft U.	very low
12	Deslauriers	U. of W. Va.	T.F.=1.35
13	Charwat	Flow Tube	very low
14	Bauer	Free Flight	vanishingly small

REF.	AIRFOIL	THICK/CHORD	AT %c	CAMBER/CHORD	AT %c
2	Pfenninger 058	.058			
3	Pfenninger 048	.048	30	.047	36
5	NACA 4412	.12	30	.040	40
7	Goettingen 803	.06	15	.07	40
	Goettingen 804	.06	36	.067	50
8	Gard Linstrom Phil.	.06	25	.069	40
9	B 6456f slotted	.064	18	.050	18
	B 8456f slotted	.084	24	.050	24
10	Geronimo wing	.080	22	.055	33
11	FX 66-S-196	.196	36	.040	43
	Eppler 385	.085	36	.050	40.5
	Eppler 387	.090	30	.040	40.5
12	Gen. Elec. No.1	.050	54	.029	54
13	Seredensky	.095	33	.044	33
14	Bauer 2 element	.060	20	.070	37.5

A-2 PERFORMANCE CALCULATION

A preliminary design of an A-2 incorporating the Pf 4.2 36-4.8 30 airfoil has been conducted and the still air performance computed. The special problems of gust response and towing problems is outside the scope of this study but must be considered later in the design of an actual contest model. Only the most rudimentary structural checks have been made. The thin section can be made strong enough within the weight allowance. The new materials should provide enough stiffness to avoid unacceptable deflections and flutter, but again this should be carefully explored before building the contest model.

In the first study it was found that the lowest wing loading provided the minimum sinking speed, since the tripped airfoil can be kept super-critical down to the Reynolds numbers associated with the lowest flight speed. Likewise it was found that the aspect ratio could be run up to at least 20 to minimize sinking speed for the same reason. One gives up a little in L/D at the lowest wing loading, but sinking speed is the name of the game. These results are plotted in Fig. 5.

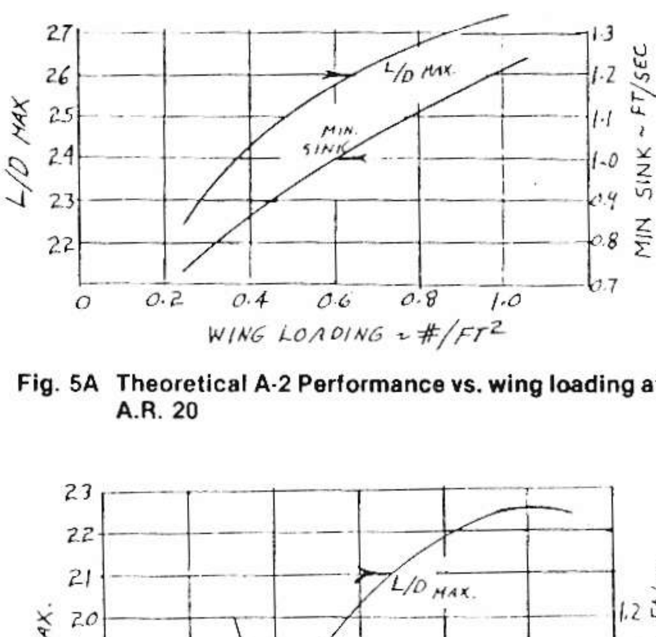

Fig. 5A Theoretical A-2 Performance vs. wing loading at A.R. 20

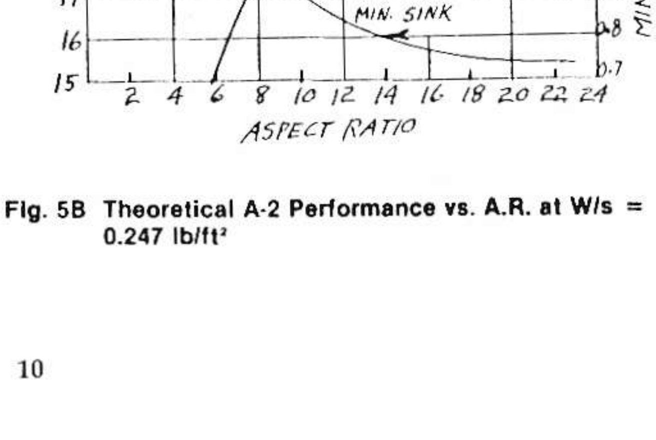

Fig. 5B Theoretical A-2 Performance vs. A.R. at W/s = 0.247 lb/ft²

The studies assumed a horizontal tail area of 15% of the wing area. A clean slender fuselage was assumed. The parasite drag breakdown is as follows:

Item	C_D Based on Wing Area
Fuselage	0.0015
Horiz. Tail	0.0008
Vert. Tail	0.0003
Intersections	0.0004
Gremlins	0.0008
	0.0030

The parsite drag coeff. of 0.003 was assumed constant in all the calculations. It could have been adjusted for RN but that comes under the heading of milking the mouse!

At the lowest wing loading, and with aspect ratio of 20, the wing chord RN is only 35,000. Even with the restricted flight lift coefficient of 0.77, the glide ratio is 22.4 and the sinking speed is a phenominal 0.736 ft/sec.

In perfectly still air, a launch from a 164 foot tow line with no zoom would result in a flight of 3.7 minutes. It may take a few tries to learn to use the properties of this airfoil, but it would seem the way to go to find the legendary 3 minute A-2 design. Those who consider this paper the mad raving of a nut who has never flown a contest, are referred to Figure 6.

It is interesting that Andrew B. Bauer in his 1975 symposium paper (Ref. 14) suggested going even further in the laminar flow low C_L direction. He studied airfoils with such low adverse pressure gradients that Laminar separation would not occur at any Reynolds number, and trippers were not required. The lift coefficients were, however, restricted to about 0.5. The performance is equivalent to the GLP and inferior only to the Pfenninger section in L/D at RN of 40,000. At a Reynolds number of 10,000 it is superior to the Pfenninger section. The sinking speed parameter is down with the Kraemer data at 40,000, but once again, appears to be the best section for use at RN of 10,000.

IN QUEST OF EVEN HIGHER PERFORMANCE

It is fascinating to contemplate whether the accumulated theoretical and experimental experience since 1956 could lead to a section superior to the Pfenninger at 35,000 RN. An excellent summary of the promise and the problems of applying modern theoretical airfoil design to the model airplane regime has been presented by Russell (Ref. 15). Extensive theoretical model airfoil developement has been done by Eppler of Stuttgart (Ref. 16). Portions of the problem associated with laminar separation, with and without trips, require solution of the Navier Stokes equations without any simplifying assumptions. This, at last, has been done in 1972 by S.K. Laine at Helsinki U, for the case of a step in a flat plate (Ref. 17). The computer requirements must be formidable. Perhaps an engineering WAG based on knowledge of the nature of the flow with some judicious constants supplied by a few definitive experiments may also do the trick, as long as the constants have been found and are only applied in the RN range of interest to us. Monson has provided considerable emperical guidance for model airfoil design (Ref. 18).

To influence the models of the future we must provide experimental checks of the theory each step of the way, as has been superbly done by Dr. F.X. Wortmann (Ref. 19) of Stuttgart for man-carrying sailplanes. The requirements for a useful experiment are not easy to meet, but can be done. The wind tunnel must have a very low turbulence level and preferably a 2 dimensional test section which also has smoke stream equipment for flow visualization. It should be possible to measure accurately the pressure distribution, transition location by stethescope probe, drag by wake survey, and lift and moment either by balance or integration of pressure distributions.

Final proof of the pudding is in free flight of a complete high performance model. Here the air mass motion must be zero or accurately known, if conventional techniques are used. There is now a measuring method for man-carrying sailplanes which effectively cancels the air mass motions. This method in its early development phase by Giavotto and Salvioni of Milan (Ref. 20), could perhaps be adapted to model tests. The ever increasing availability of miniaturized electronics bodes well for this approach.

We must remember that any success we may have in applying such high technology rests on a firm foundation of the work of dedicated model builders who, while perhaps lacking a full University training, were nevertheless keen and truthful observers and arrived emperically at some excellent airfoils which perform quite well in the real and fascinating world of contest flying.

So, smile if you will at the quaint machine
But not at the Gallant Clan
Which gave its heart, though it lacked the art
Or the tools for a better plan.
They reached for the stars while the savants slept
And their faith was a thing of flame
Which kindled the sky, though today they lie
Unmarked by the world's acclaim.

Gill Rob Wilson
(Ref. 21)

DEDICATION

This paper is dedicated to the man who has done more to explore the limits of low loss aerodynamics in his lifetime than all the rest of us combined. His unerring choice of the particular crucial experiment to prove the theory, nearly always results in an optimum the first time, and is cause for wonder. I suspect his success is made up of equal parts of being born a genius, continuous hard unremitting work, never doing less than one's absolute best, and an abiding interest and love for the science of flight. Dr. Werner Pfenninger, dear friend, great leader, and honored teacher, we of the model airplane fraternity salute you.

B. H. Carmichael
February 12, 1978