ANALYTICAL STUDIES OF NEW AIRFOILS FOR WIND TURBINES

W.H. Wentz, Jr., J.T. Calhoun
Wichita State University Consultant

ABSTRACT

Computer studies have been conducted to analyze the potential gains associated with utilizing new airfoils for large wind turbine rotor blades. Attempts to include 3-dimensional stalling effects are inconclusive. It is recommended that blade pressure measurements be made to clarify the nature of blade stalling. It is also recommended that new NASA laminar flow airfoils be used as rotor blade sections.

INTRODUCTION

Studies of new airfoils for wind turbine applications are being conducted at Wichita State University, in cooperation with the NASA Lewis Research Center. Current wind turbines utilize airfoil sections designed in the 1930's and 1940's from the familiar NACA airfoil series documented in reference 1. Beginning about 1975, computational techniques for fluid dynamic analysis reached a state of development which permitted rapid, low cost analysis of airfoil shapes. This capability has resulted in a number of computer designed low-speed airfoil development programs in addition to the recent better known transonic airfoil developments. Examples of the new low-speed airfoils are documented in references 2, 3 and 4.

The purpose of the current studies is to determine whether the new airfoils or as yet undesigned airfoils offer significant advantages relative to the older airfoils for wind turbine application.

WIND TURBINE PERFORMANCE

Relationship Between Airfoil Characteristics and Wind Turbine Performance

In order to design a new airfoil for wind turbine application, it is essential to understand the relationships between airfoil characteristics and turbine performance. While it is perhaps obvious that high c_l and low c_d are desirable, the performance sensitivity of the turbine to these characteristics is not obvious.

The performance changes associated with wind speed changes for constant rpm can best be understood in terms of blade section angle of attack and section airfoil characteristics. For constant rpm operation, blade section angle of attack increases as wind speed is increased, as shown in figure 1. Thus the initial response to increasing wind speed is for blade lift coefficient and power to increase. As wind speed continues to increase, the angle for maximum lift coefficient is reached, and further increase in wind speed results in blade stalling, with rapid loss of lift and increase in drag, resulting in loss of power. Thus blade section stalling limits maximum power and the wind speed at which maximum power occurs.

These studies are being conducted utilizing a WSU-modified version of the "PROP" wind turbine performance computer code, which utilizes strip analysis combined with momentum (Betz theory). Earlier studies at WSU used a specially adapted version of this computer code to study aileron and spoiler control systems as alternatives to blade pitch control (ref. 5). The present paper is a status report of the airfoil studies, which are still in progress. These studies are based upon the 125 ft diameter NASA MOD-0 turbine, with untwisted blade utilizing the NACA 23024 airfoil section. Rotation rate is 33 rpm for all cases.

Swept Area Distribution and Blade Torque

Figure 2 illustrates the area distribution versus radius for a circle. It serves to highlight the significance of careful design of the outer portions of the rotor blade, since these portions sweep through the greatest area. Figure 3 shows calculated torque as a function of radius for several wind speeds. Even when tip loss effects are included, (as in the present case) the importance of the outer portion of the blade in producing power is evident. Thus if new aifoil sections for improved power output are to be designed for only a portion of the span, attention must be focused on the outer portion of the blade.

Parametric Studies of Airfoil Section Characteristics

Parametric variation of aerodynamic characteristics provide an excellent tool for increased understanding of the somewhat subtle relationships between airfoil characteristics and wind turbine performance. Airfoil characteristics can be summarized as follows. Lift coefficient depends primarily upon camber and angle of attack. In order to obtain good are aerodynamic performance, it is necessary to have unseparated flow. The camber of the section is the primary parameter which controls the lift coefficient at which separation and stalling occur, at least for medium thickness sections (10% t/c or more). Section lift curve slope is essentially independent of camber and thickness. For low Mach number conditions, maximum lift coefficient is obtained for sections having thickness ratios of about 12% to 15%. Section drag coefficient depends primarily on Reynolds number, thickness, portion of laminar flow (if the surface is smooth enough), camber, and lift coefficient.

Section Drag Coefficient Studies

Figure 4 shows the results of studies of wind turbine performance for parametric changes in airfoil section drag minimum drag coefficient. This figure shows that doubling the section minimum drag without changing the lift characteristics results in a power loss which is approximately constant for all wind speeds, about 16 kW for this machine. Reducing the minimum section drag coefficient by 50% results in a nearly constant power increase of about 8 kW for this machine. These results illustrate that the "parasite power" of the turbine is essentially a function of blade area and rpm, and is therefore affected only slightly by wind speed.

These preliminary drag change studies were refined by calculating the drag changes associated with changes in airfoil thickness. Thickness affects section drag as shown in equation 1 from reference 6.

$$c_d = c_{d_{t=0}}(1 + 2\ t/c + 60\ t/c^4) \qquad (1)$$

This equation was used along with the basic 24% thick NACA 23024 data to calculate minimum section drag for a 12% thick NACA 23012. This result was used to make the computer runs shown in figure 5. Decreasing blade thickness to 12% over the full span results in a power increase of about 10 kW, while decreasing the thickness only from 70% radius to the tip results in about 8 kW power increase.

Section Lift Coefficient Studies

A series of runs were made in which a constant increment in lift was added to the standard airfoil characteristics. This study is designed to assess the importance of blade section camber on turbine performance. The results of this study are shown in figure 6. For moderate and high wind speeds, increasing the lift coefficient provides substantial power increases, as expected. At low wind speeds (6 m/s and lower), lift coefficient increments of 0.1 and 0.2 have little effect, while Δc_l values of 0.4 and 0.6 show substantial power gains. The gains in power at the very low wind speeds are surprising and are viewed with some skepticism. As a check on the computer results, a theoretical line for c_p = .59 (Betz limit) has been added to the graph. The computer results which exceed the Betz limit are invalid. Detailed printout for these runs shows that the slowdown factor (wind velocity reduction through the rotor) has not properly converged for cases for which the power coefficient has exceeded the Betz limit. At higher wind speeds, proper convergence in the slowdown factor iteration loop has been achieved, and the results are accepted with less skepticism. In reviewing the results of the drag and lift parametric studies, it becomes apparent that increases in camber (added c_l) are very promising.

Studies of Advanced Airfoils

To illustrate the potential gains in performance associated with advanced airfoils, computer studies have been conducted utilizing a new NASA-Langley low-speed airfoil designed to achieve a substantial portion of laminar flow. This airfoil has a high design lift coefficient, and has very low drag levels at lift coefficients from 0 to 1.2. The airfoil has a 15% thickness to chord ratio. A constraint on this particular airfoil design was to minimize penalties associated with loss of laminar flow due to surface roughness. This objective has been achieved to a remarkable degree, to the extent that with roughness applied to the airfoil, no loss in $c_{l_{max}}$ occurs, but only an increase in drag.

The appropriateness of selecting a laminar flow airfoil for application to wind turbine rotor is subject to question. Nevertheless, the authors believe that with blade fabrication techniques which insure a smooth, hard surface, proper finishing techniques, and occasional rotor washing on low-wind days to remove dirt and insect accretion, laminar flow can be achieved. The new-technology airfoils permit taking advantage of laminar flow when possbile, without the fear that a dirty or wrinkled blade will create intolerable performance penalties.

The predicted performance of the MOD-0 turbine based upon the new natural laminar flow airfoil is shown in figure 7. The performance gain associated with this airfoil seems quite remarkable, but are in fact consistent with gains illustrated earlier for similar levels of parametric section c_l and c_d variation. Even if laminar flow is not attained, the performance gains are quite large. Unfortunately, the problem noted earlier of computer calculation non-convergence for low wind speeds is again present.

Comparison Between Experiment and Theory

Since the primary objective of utilizing improved airfoils on wind turbines is to achieve performance gains, it is essential to have an analytical model which is capable of predicting actual performance with a reasonable degree of accuracy. Obtaining accurate experimental measurements is complicated by the need to test at full scale for proper Reynolds number matching and the problems associated with full scale field testing, such as: non-steady-state conditions, difficulties in obtaining accurage wind speed information, and uncertainties associated with generator efficiencies and drive train power losses.

A new technique for analyzing experimental full scale wind turbine data is being developed at NASA Lewis. This technique utilizes the method of bins for sorting the experimental samples, and special calibrations of the wind speed instrumentation from several sensors. This work is still in progress, and the results will be reported later. It is hoped that these studies will provide more definitive measurements of shaft power versus wind speed than are presently available.

Three-Dimensional Stalling Effects

Himmelskamp (ref. 7) performed experiments in which pressures were measured at a number of stations between 40% and 80% span on a rotating blade. His experiments (fig. 8) show that stalling tends to be delayed over most of the rotating blade relative to the two-dimensional case. This effect is attributed to centrifugal forces acting on the boundary layer flow. While Himmelskamp made no measurements beyond 80% span, extrapolation of his data indicates that characteristics at 90% span would correspond closely to the two-dimensional case, and stations from 90% to 100% span would have lower stalling angle and $c_{l_{max}}$ than the two-dimensional case.

In addition to the changes in stalling angle and $c_{l_{max}}$ which Himmelskamp observed, corresponding changes in drag must also occur. Unfortunately, Himmelskamp's drag measurements were not accurate enough to use for performance prediction for arbitrary airfoils.

In order to apply the Himmelskamp data to rotors of arbitrary geometry,it was necessary to extract a series of generalized characteristics from the Himmelskamp data. Parameters selected were the ratio of $c_{l_{max}}$ 3D to $c_{l_{max}}$ 2D, stalling angle in three dimensions to the stalling angle in two dimensions, and a series of parameters to model an assumed section drag coefficient behavior for three dimensions. The drag model assumes one parabolic form for the c_d vs alpha relationship prior to stalling, and a second parabolic equation for the drag curve from initial spearation to full separation. Initial separation angle, stalling angle and full separation angle become functions of radial station. Modeling the c_d relationship in three dimensions then becomes rather straightforward based upon modified angles for initial separation and stalling. The three-dimensional effects are treated as corrections to the two-dimensional data, so that the analytical model can be applied to any set of two-dimensional airfoil data in the PROP program.

Figure 9 shows predicted performance for the NACA 23024 airfoil section including the Himmelskamp three-dimensional effects. Figure 10 shows power predicted for the NASA MOD-0 turbine using the Himmelskamp three-dimensional stall prediction technique just described. This analysis shows that the predicted peak power has increased greatly, and now exceeds measured maximum power by a substantial amount. The discrepancy is so large that it casts doubt on all calculations with codes of this type which do not include 3-D stalling effects. It is very likely that the low-Reynolds number Himmelskamp experiments lead to over-prediction of the 3-D effects. Nonetheless, the potential effects are too large to be ignored. Even if the actual effects are only 50% of those predicted, the effects are still as large as the possible changes in performance between a poor (NACA 23024) airfoil and high-performance airfoil.

Need For Large Scale Blade Pressure Measurements

Further improvements in power prediction are not likely without determining power and wind speed with greater accuracy, and/or determining blade section stalling characteristics of a rotating turbine. Making blade pressure distribution measurements of a rotating full scale turbine would provide answers to the blade stalling questions, as well as providing checks on blade structural load prediction techniques, which rely on the same analytical models as the performance estimates. For these reasons, the authors are recommending that an experimental program be undertaken to measure pressures at a number of blade stations on the MOD-0 machine.

CONCLUSIONS

1. Analytical methods such as the PROP code need to be improved to provide proper convergence even for low wind speed, high section c_l cases.

2. Pressure measurements are needed on a large scale wind turbine to understand the nature of blade stalling in three-dimensions, and to aid in developing improved theoretical models.

3. Wind turbines should utilize advanced low-speed airfoils to take advantage of possible performance gains which do not add to blade cost.

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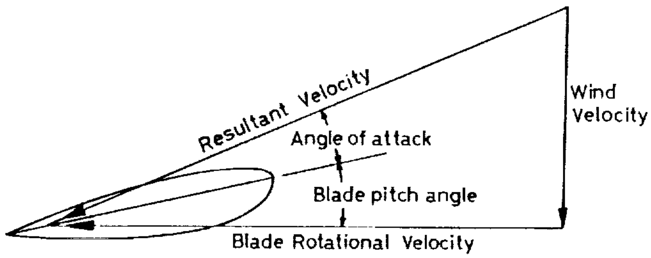


Fig. 1- Blade Section Angles.

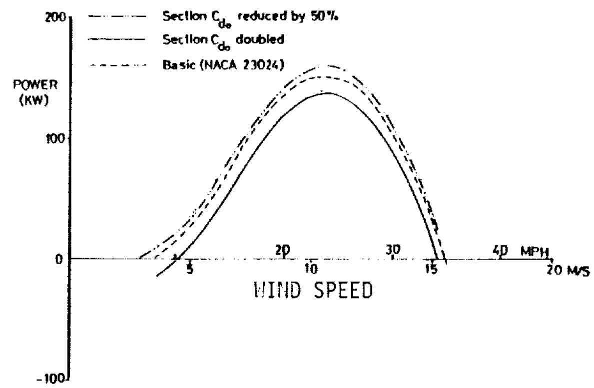


Fig. 4- Effects of c_{do} Changes on Wind Turbine Performance.

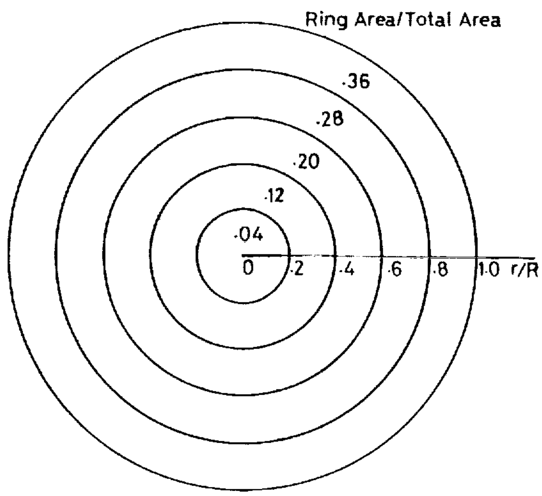


Fig. 2- Blade Swept Area Distribution.

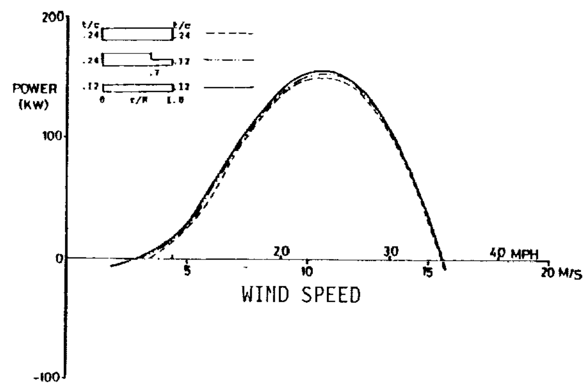


Fig. 5- Effects of Airfoil Thickness Changes on Wind Turbine Performance.

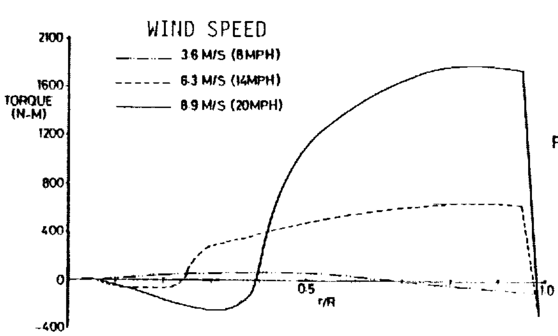


Fig. 3- Blade Torque Distribution.

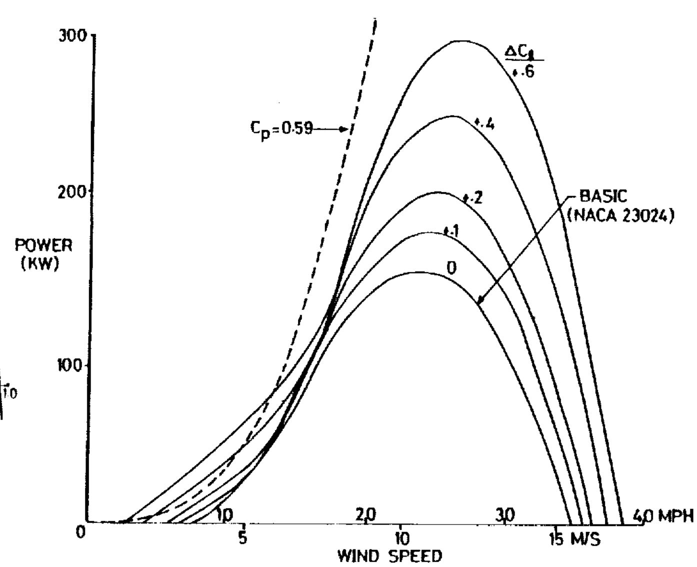


Fig. 6- Effects of Δc_l on Wind Turbine Performance.

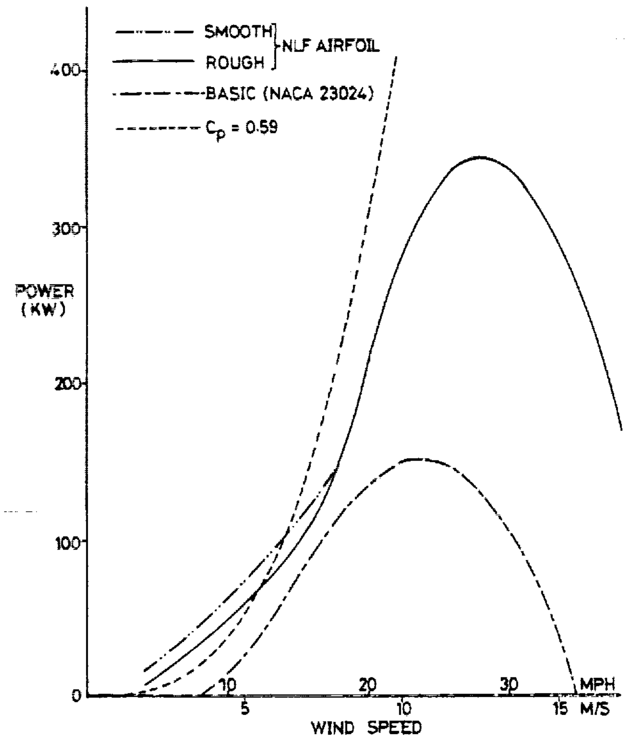
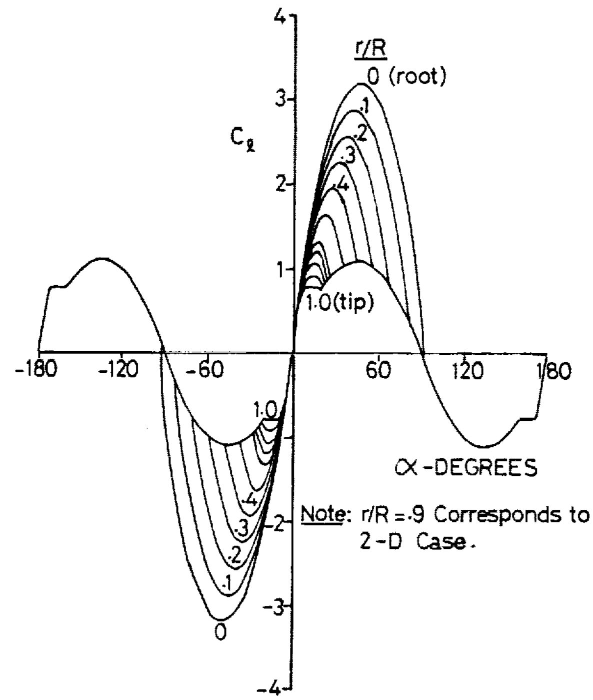


Fig. 7- Performance with New Laminar Flow Airfoil.



(a) Lift

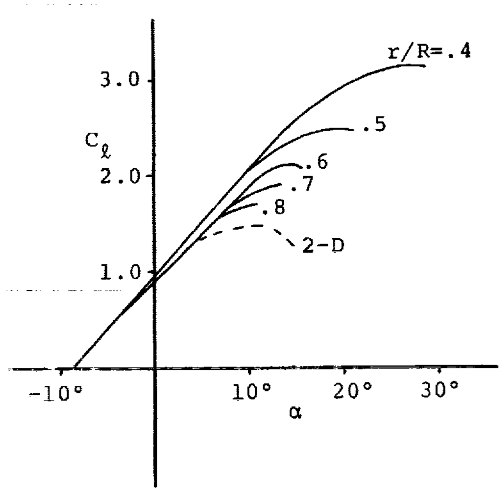
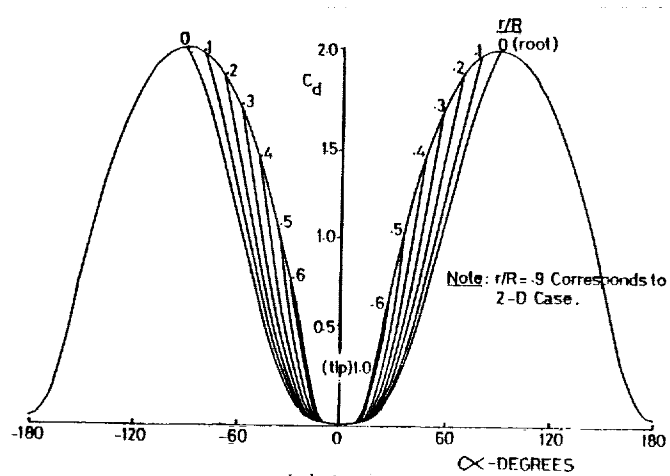


Fig. 8- Himmelskamp's Experiments.



(b) Drag.

Fig. 9- Effects of 3-D Stalling on NACA 23024 Airfoil

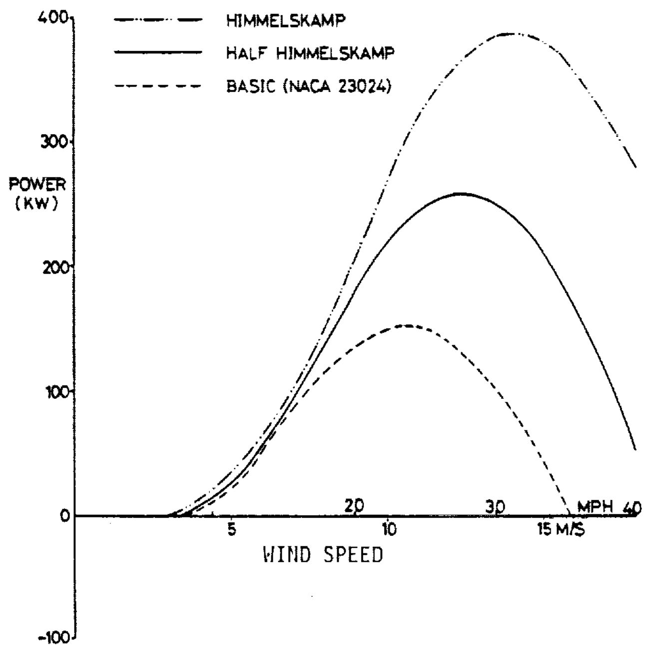


Fig. 10- Effects of 3-D Stalling on Wind Turbine Performance.

QUESTIONS AND ANSWERS

W.H. Wentz

From: A.D. Garrad

Q: Are you aware of Wortmann's work on laminar airfoils where he covers the section with a thin plastic sheet? This "bounces off" insects and dirt but remains smooth. This has been used successfully in realistic environmental conditions.

A: *I was not aware of Wortmann's specific work in this area, but have understood that materials are available which minimize "sticking" of bugs and other substances. These same surfaces are cleaned more easily than traditional materials.*

From: G. Beaulieu

Q: (Related to parametric study) - When you increased C_L, did you compute a proportional increase in induced drag before computing the power output in order to get realistic two-dimensional airfoil data?

A: *No. While this technique has been suggested by some researchers (I believe by Mr. Viterna of NASA Lewis Research Center), I do not believe that it has a theoretical basis. The induced velocity factors "a" and "a-prime" as used in the PROP computer code serve a purpose similar to calculating downwash on a finite span wing. Application of Glauert's momentum theory accounts for induced power in a manner analogous to Prandtl's induced drag factor for finite span wings. If some additional correction factor is needed to match experimental results, I would prefer to identify the factor as an empirical correction rather than obscure it as a theoretical correction, which it is not.*

From: T.E. Base

Q: In your figure, "Power - Flow Speed," do you exceed the Betz Limit with your laminar flow airfoil section if looked as if there was a 250% increase in performance?

A: *The laminar flow airfoil performance exceeds the Betz limit at low wind speeds, as shown in Figures 6 and 7. At wind speeds below, the "a" slowdown factor did not converge satisfactorily or exceed 0.5 which implies reverse flow in the far field. These are the limitations I tried to highlight in the presentation. For moderate and high wind speeds, convergence was satisfactory, and C_p values are well below the Betz limit.*

At speeds near cut-in, performance gains in excess of 100% will be possible (infinite, if we reduce the cut-in speed by reducing section C_{d_o}), but we need a code which will properly converge at these low wind speed, moderate C_l conditions.

From: A. Smith

Q: Did you consider radial variations in airfoil, camber, thickness, etc.?

From: M.P. Moriarty

Q: PROP has provision only to handle one airfoil section at a time. Have you modified PROP to accommodate varying sections and if so, how did you verify the code change?

A: (to both questions above). *We have modified the PROP code so that we can branch to different airfoil characteristic subroutines as a function of radial position. In this way, it is possible to charge airfoil characteristics as desired. We have used, at one time, a special model in which we calculate minimum C_{d_o} as a function of t/C. Ordinarily, it is necessary to insert the lift and drag characteristics of the specific airfoil you desired to study. These coding changes have been "verified" in the sense that we have made careful check runs with detailed printout at each radial station. From these runs, we check the C_l and C_d versus alpha at each station to insure that our airfoil coefficient tables have been properly input and are being properly called.*

From: T.A. Egolf

Q: Do you feel that for small WECS, improving airfoil performance is worthwhile from a Cost of Energy (COE) point of view?

A: *Yes. I am eager to see someone utilize the new airfoil technology on a small unit. It would be quite important to obtain accurate comparative performance data to establish the performance gains which the PROP code is predicting. One possible cost effective way to make such an evaluation, is to conduct "back-to-back" tests with standard and new blades. This should be possible on a small unit without excessive cost.*

From: Anonymous

Q: Is the technology to manufacture these blades presently available?

A: *Manufacturing techniques exist which are capable of providing surfaces which are both smooth enough and hard enough to give large areas of laminar flow, yet are neither highly exotic nor hard to use. Maintaining laminar flow under field conditions will require periodic cleaning. Whether periodic washing and waxing (?) is cost effective is a matter which I believe deserves attention.*

From: D. Cromack

Q: How does laminar flow affect the start-up (since it is often at such low Reynolds number)?

A: *Even though we have no wind tunnel data for Reynolds numbers corresponding to start-up, I see no reason that new laminar flow sections should be a problem. We have little or no data on the older (presently used) sections for these conditions, and they can be aerodynamically started. I do believe that a legitimate need exists for airfoils designed to operate at Reynolds numbers of less than* 1×10^6, *for small wind turbine application.*

From: F.W. Perkins

Q: What is the maximum power coefficient predicted under three-dimensional flow conditions by PROP?

A: *As indicated on Figures 6 and 7, for low wind speeds, the computer program predicted* C_p *values in excess of the 0.59 Betz limit. This did not occur for the baseline NACA 23024 airfoil, but was encountered for airfoils with substantial camber (higher* C_d*'s at low angle of attack). In such cases, values of* C_p *in excess of 1.0 are frequently obtained. The paper by Professor Jeng seems to resolve this problem, and we plan to upgrade our computer code to incorporate his method.*

From: J. Landgrebe

Q: Do you really think that laminar flow can be maintained in the real wind environment (unsteady turbulent flow)?

A: *Under highly gusty conditions, laminar flow will not be possible. On the other hand, some atmospheric conditions and sites will permit periods of laminar flow, and the potential gains are attractive enough to pursue. Even if laminar flow is never attained with these airfoils, their performance as turbulent sections is excellent. Our studies on this matter are not yet complete, but I am having a hard time finding a better turbulent flow airfoil.*

From: J. Tangler

Q: What kind of laminar flow airfoil are you talking about? Do they depend on leading edge suction or aft camber?

A: *These airfoils do not require artificial powered suction, if that's what you are referring to. The laminar flow is achieved through pressure distribution control by means of the airfoil shape.*

From: D.C. Shepherd

Q: Are the results of your study presently published or must we wait for the proceedings of this workshop? Please identify any papers already published.

A: *Our earlier aileron control system studies were published in reference 5. This meeting is the first publication of application of new airfoils to wind turbines. Some of the airfoil data developed at the NASA Langley Research Center have not yet been published in the open literature, but I understand the data will be released soon, at least to U.S. based firms and agencies.*