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STATUS OF THE SPECIAL-PURPOSE AIRFOIL FAMILIES

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ABSTRACT

This report describes work sponsored by the U.S. Department of Energy (DOE) under Contract No. DE-AC02-83CH10093. The work is directed at developing thin and thick airfoil families, for rotors with diameters of 10 to 30 m, that enhance annual energy output at low to medium wind speeds and provide more consistent operating characteristics with lower fatigue loads at high wind speeds. Performance is enhanced through the use of laminar flow, while more consistent rotor operating characteristics at high wind speeds are achieved by tailoring the airfoil such that the maximum lift coefficient $C_{l,max}$ is largely independent of roughness effects.

Using the Eppler airfoil design code, two thin and one thick airfoil family were designed; each family had a root, outboard, and tip airfoil. Two-dimensional wind-tunnel tests were conducted to verify the predicted performance characteristics for both a thin and thick outboard airfoil from these families. Atmospheric tests on full-scale wind turbines will complete the verification process.

NOMENCLATURE

c	chord
c_d	drag coefficient
C_l	lift coefficient
C_m	pitching-moment coefficient at quarter chord
C_{mo}	pitching-moment coefficient at zero lift
d	drag
l	lift
r	local rotor radius
R	total rotor radius
t	airfoil thickness
max	maximum
min	minimum

INTRODUCTION

Two significant problems that adversely affect the economics and reliability of wind-turbine blades have been identified at the many California wind farms. The first problem involves the inadequate energy capture resulting from using airfoils that were designed for fixed-wing aircraft. The second problem involves inadequate blade structures resulting from deficient structural designs and poor quality control during the manufacturing process. Because of these problems, one of the most significant business opportunities over the next several years will be in the blade-replacement market (over 5000 sets of blades are expected to be replaced). The next generation of retrofit blades is expected to provide substantial improvements in energy capture, blade life, and cost relative to blades currently being used on wind turbines. This paper reports progress on the solution to the first problem (using airfoils designed for aircraft), or, specifically, improving the transfer function between the wind input and the blade structure. These special-purpose airfoil families are expected to provide the improved energy capture and operating characteristics needed for the upcoming second-generation rotor blades.

Under the Solar Energy Research Institute's (SERI) Special-Purpose Airfoil task, three airfoil families have been designed for use on rotors 10 to 30 m in diameter. Two of these families are designated thin airfoil families, while the third is designated a thick airfoil family. The thin airfoil families are targeted more for fiberglass blades, while the thick airfoil family is targeted more toward wood composite blades. The distinguishing feature between the two thin airfoil families is that one is designed to have a high $C_{l,max}$ over the outboard portion of the blade. Rotors with fixed-pitch blades and that operate at wind sites having high mean annual wind speeds can benefit in annual energy output when the outboard portion of the blade has a high $C_{l,max}$. At sites with more typical mean annual wind speeds of 5.4-6.3 m/s (12-14 mph), a high $C_{l,max}$ over the outboard portion of the blade is not needed and may increase machine cost and fatigue. Peak power is proportional to the $C_{l,max}$ of the airfoil over the outboard portion of th blade. Using an airfoil with a larger $C_{l,max}$ than the wind site warrants results in increased generator costs, transmission oversizing, and greater structural requirements to accommodate the peak rotor load. The airfoil design criteria for the thick airfoil family with a low $C_{l,max}$ outboard are the same as those of the thin airfoil family with a low $C_{l,max}$ outboard. The 50% increase in airfoil thickness for the thick airfoil family helps accommodate the more demanding structural requirements of the wood composite and the larger blades.

DESIGN APPROACH

The five-step design approach used for developing the special-purpose airfoil families is shown in Figure 1. Step 1 involved identifying the initial design specifications thought to provide the desired performance characteristics. Two important initial requirements were that the new airfoils had (1) a $C_{l,max}$ that was relatively insensitive to roughness effects, and (2) higher lift/drag (l/d) ratios for greater annual energy output. Based on the initial design requirements, Step 2 in the design process was to use the Eppler airfoil design code [1] to design the first family of thin airfoils (S801, S802, S803, S804). Step 3 was to analytically simulate a wind turbine operating with the first airfoil family, with a representative generator, transmission efficiency, and wind distribution. For this purpose, SERI's Systems Engineering and Analysis Computer Code (SEACC) [2] was used to calculate a performance curve and annual energy output. The results of this process verified that higher l/d ratios can result in a noticeable improvement in annual energy output. However, the more interesting observation was that peak power for a fixed-pitch rotor will increase substantially if the $C_{l,max}$ of the blade's outboard airfoils is not checked. For wind sites having high mean annual wind speeds, the increase in peak power may present no problem. However, for sites with winds of 5.4 to 6.3 m/s (12 to 14 mph), the high peak power may lead to higher machine cost and fatigue loads. Based on this observation, the initial design specifications were expanded to those that follow for designing the next two airfoil families.

<u>**Design Specifications for Sites with Medium Wind Speeds**</u>

- Reduced peak power sensitivity to airfoil insect accumulation for greater annual energy output is obtained through minimizing the sensitivity of the $C_{l,max}$ to leading-edge roughness.
- Greater annual energy output at sites with medium wind speeds (5.4-6.3 m/s [12-14 mph]) is achieved with the maximum l/d ratio at a medium value of C_l for the outboard airfoils.
- Lower fatigue loads, resulting in longer blade life, are achieved through a continuous decrease in $C_{l,max}$ from the root to the tip.

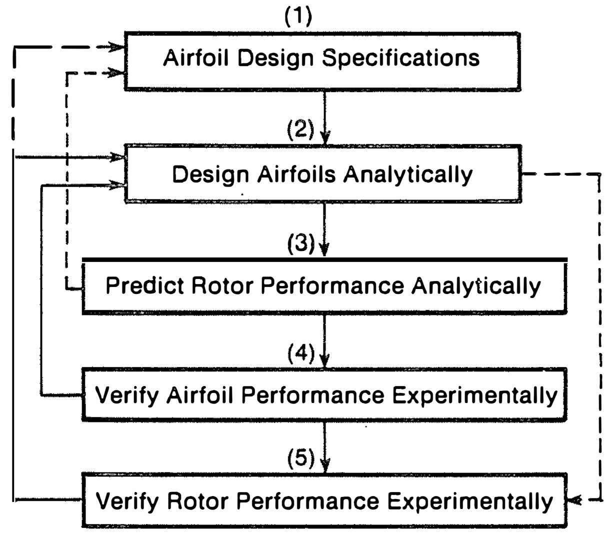

Figure 1. DESIGN APPROACH FOR THE SPECIAL-PURPOSE AIRFOIL FAMILIES

Using the above criteria, a second thin airfoil family (S805, S806, S807, S808) was designed to limit peak power. The primary airfoil (S805) of this thin airfoil family was used to proceed on to Step 4 in the design process. Step 4 involved verifying the predicted performance characteristics of the S805 against two-dimensional wind-tunnel measurements [3]. This comparison identified a bias error in the Eppler airfoil design code. The S805 was originally designed for a Reynolds number of 1×10^6. However, wind-tunnel tests showed significant drag-producing laminar-separation bubbles on the upper and lower surfaces for this condition; the bubbles gradually disappeared for higher Reynolds numbers. These tests showed the airfoil to be better optimized for Reynolds numbers of 2×10^6 and above. An adjustment to the design Reynolds number was made to accommodate this bias error. The adjustment consisted of checking the significance of the laminar separation bubbles of subsequent airfoils at a Reynolds number of about one-half the intended Reynolds number. The S805A and S806A were then designed to replace the S805 and S806 at the intended Reynolds number of 1×10^6. The final step in the design process (Step 5) involves atmospherically testing each airfoil family. Preparations are currently under way to atmospherically test the thin airfoil family (S805A, S806A, S807, and S808) with a restrained $C_{l,max}$ outboard on the blade. These tests will provide the final measure as to what degree these new airfoils achieve their design objectives, as well as provide any further guidance on the design specifications.

Following a path similar to that of the latter thin airfoil family, a thick airfoil family (S809, S810, S811) was also designed. The performance characteristics of the primary member of this family (S809) were verified, through two-dimensional wind-tunnel tests, and were found to be in good agreement with predictions. A second iteration of this family is currently being completed to increase the $C_{l,max}$ of the outboard airfoils by 0.2. This second iteration should be better suited for California wind sites, while the original thick airfoil family appears best suited for sites having low mean annual wind speeds.

THREE AIRFOIL FAMILIES

The key design parameters for the airfoils that comprise each airfoil family are shown in Tables 1 through 3. The reference blade radial station r/R, for which the airfoil was designed, is listed in the second column. The primary radial station is 0.75. Most of the design effort for each airfoil family is associated with this station. Radial station 0.95 is designated the tip airfoil station, while radial stations equal to or less than 0.4 are designated as blade root airfoil stations. The corresponding Reynolds number for each blade station, accounting for rotor size, is listed in the third column of the tables. The fourth column lists the airfoil thickness t/c, which decreases in a relatively linear manner from the blade root to the blade tip. Although it is desirable for the root airfoils to have a high $C_{l,max}$ (shown in the fifth column), their low local Reynolds number and greater thickness make it difficult to achieve a $C_{l,max}$ greater than those values indicated. The sixth column lists each airfoil's minimum drag coefficient $C_{d,min}$, which occurs around zero lift. The $C_{d,min}$ depends largely on the extent of laminar flow over the airfoil. The values listed may be lower than those achieved on actual blades if manufacturing tolerances cannot be accurately controlled. The moment coefficient for zero lift C_{mo} is listed in the last column; actual values for a loaded rotor may differ slightly from than those listed.

TABLE 1. DESIGN PARAMETERS FOR THE THIN AIRFOIL FAMILY (HIGH $C_{l,max}$)

Airfoil	r/R	Reynolds No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S801	0.75	2.0	0.135	1.65	0.007	-0.15
S802	0.95	2.6	0.115	1.68	0.006	-0.15
S803	0.95	2.6	0.115	1.68	0.007	-0.15
S804	0.30	0.8	0.180	1.60	0.120	-0.15

TABLE 2. DESIGN PARAMETERS FOR THE THIN AIRFOIL FAMILY (LOW $C_{l,max}$)

Airfoil	r/R	Reynolds No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S805	0.75	2.0	0.135	1.29	0.005	-0.05
S806	0.95	2.6	0.115	1.10	0.004	-0.05
S807	0.30	0.8	0.180	1.46	0.010	-0.10
S808	0.20	0.8	0.210	1.30	0.012	-0.12
S805A	0.75	1.0	0.135	1.20	0.007	-0.05
S806A	0.95	1.3	0.115	1.10	0.006	-0.05

TABLE 3. DESIGN PARAMETERS FOR THE THICK AIRFOIL FAMILY (LOW $C_{l,max}$)

Airfoil	r/R	Reynolds No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S809	0.75	2.0	0.210	1.00	0.007	-0.05
S810	0.95	2.0	0.180	0.90	0.006	-0.05
S811	0.40	1.0	0.260	1.30	0.012	-0.12
S812	0.75	2.0	0.210	1.20	0.008*	-0.07*
S813	0.95	2.0	0.160	1.10	0.007*	-0.07*

*Target values.

Thin Airfoil Family (with High $C_{l,max}$)

This airfoil family was the first of the three to be designed, with a $C_{l,max}$ that is relatively insensitive to leading-edge roughness. The airfoil thickness was kept low to achieve a high l/d ratio. No constraint was placed on the airfoil's pitching moment so that the $C_{l,max}$ of all the airfoils in the family could be maximized. This airfoil family is suitable for rotors 20 m in diameter and larger.

The airfoil shapes for this family are shown in Figure 2, and the respective design parameters for each airfoil are listed in Table 1. The S801 is the primary airfoil (r/R = 0.75) and warrants most of the design effort. The two tip airfoils (S802 and S803) and the root airfoil (S804) complement the primary airfoil and provide a linear reduction in airfoil thickness from the blade root to the tip. The two tip airfoils differ in one subtle aspect. The S802 has a slightly lower $C_{d,min}$ than does the S803; however, the S803 has a slightly wider drag bucket. With leading-edge roughness, the performance characteristics of the S802 and S803 are almost identical. The thicker S804 airfoil is designed for a high $C_{l,max}$ at a low Reynolds number. To achieve a high $C_{l,max}$ at the root, the requirement that $C_{l,max}$ be insensitive tc

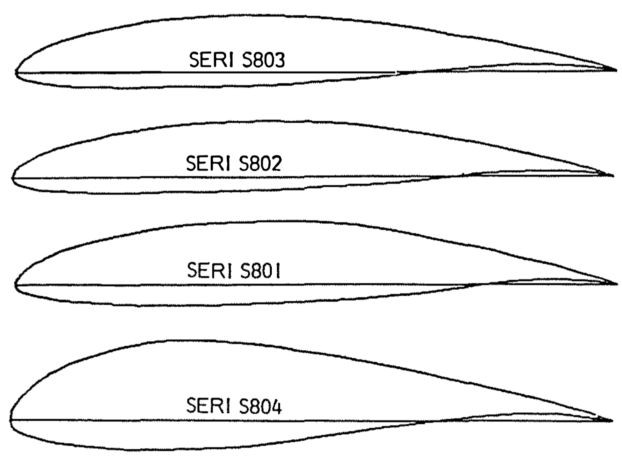

Figure 2. THE THIN AIRFOIL FAMILY (HIGH $C_{l,max}$)

roughness effects was dropped. This requirement is not necessary at the blade root, where the airfoils have no influence on peak power.

This thin airfoil family is expected to be used primarily at wind sites having high mean annual wind speeds. The high $C_{l,max}$ allows the designer to use a smaller blade chord or lower rotor solidity in situations where parked rotor loads are a major contributor to blade failures. However, to accommodate the airfoil family's high pitching moment, the blade's torsional stiffness must be adequate to avoid significant elastic twist.

Thin Airfoil Family (with Low $C_{l,max}$)

This airfoil family was developed because the $C_{l,max}$ over the outboard portion of the blade is undesirable at wind sites with a mean annual wind speed of 5.4 to 6.3 m/s (12 to 14 mph). However, toward the blade root, a high $C_{l,max}$ is desirable for any wind site. In addition to having a low airfoil thickness, the pitching moment of this family was not to exceed a negative value of 0.05 over the outboard portion of the blade. To achieve a high $C_{l,max}$ for the root airfoil, the airfoil's pitching-moment constraint was relaxed to a negative value of 0.10. Although the outboard airfoils of this family are designed to have a $C_{l,max}$ that is insensitive to roughness effects, this requirement was unnecessary for the root airfoil. This airfoil family is suitable for rotors with 10- to 30-m diameters.

The airfoils for this family are shown in Figure 3, and the respective design parameters for each airfoil are listed in Table 2. For rotors in the 10-m-diameter range, the primary airfoil is the S805A (used in conjunction with the S806A tip airfoil and the S807 root airfoil). The S805A and S806A airfoils provide a more favorable pressure recovery for a Reynolds number of 1×10^6 to prevent laminar separation bubbles. For rotors 20 m in diameter and larger, the primary airfoil is the S805 (used in conjunction with the S806 and S807). The S808 airfoil is available for blades of all sizes that require additional root thickness.

Thick Airfoil Family (with Low $C_{l,max}$)

The thick airfoil family satisfies the need for greater airfoil sectional stiffness for larger or wood veneer blades. This airfoil family is 50% thicker than the thin airfoil family at each radial station along the blade span. The desired airfoil design parameters are similar to those for the thin airfoil family with a low $C_{l,max}$ outboard on the blade. As the most recent of the airfoil families, it presented the greatest design challenge because of its thickness. This thickness makes it difficult to achieve high l/d ratios. In spite of this design difficulty, the airfoil family has an l/d ratio equal to or greater than that of other airfoils of this thickness and Reynolds number. Based on the design Reynolds number, this airfoil family is suitable for rotors 20 m in diameter and larger.

The thick airfoil family is shown in Figure 4, and the respective design parameters for each airfoil are listed in Table 3. Two primary airfoils (S809 and S812) and two tip airfoils (S810 and 813) are given in the table. The distinguishing difference is that the S812 and S813 airfoils have a $C_{l,max}$ 0.2 greater than that of the S809 and S810. For most wind sites, the S812 and S813 would be the preferred choice. The S809 and S810 may only be for sites having mean annual wind speeds of 5.4 m/s (12 mph) or less. Atmospheric tests are needed to better quantify the suitable wind-speed range. One root airfoil, the S811, is indicated for both sets of outboard airfoils. For its thickness of 26%, the $C_{l,max}$ of 1.3 is considered substantial. To achieve this value, the moment coefficient was unrestrained and resulted in a negative value of 0.12. An attempt to design good airfoil characteristics into root sections of greater thickness was futile.

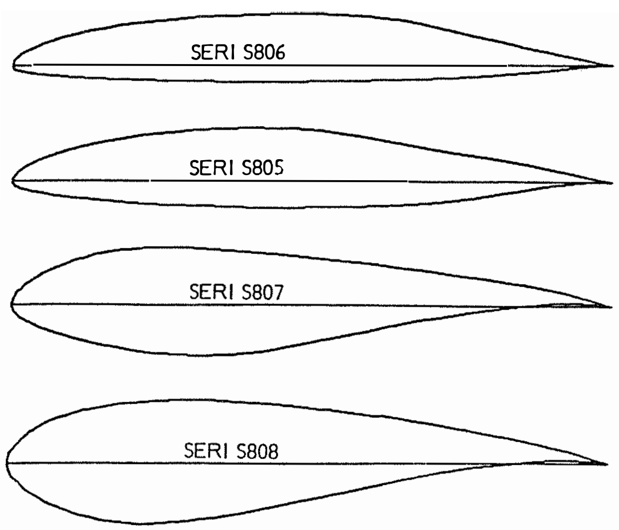

Figure 3. THE THIN AIRFOIL FAMILY (LOW $C_{l,max}$)

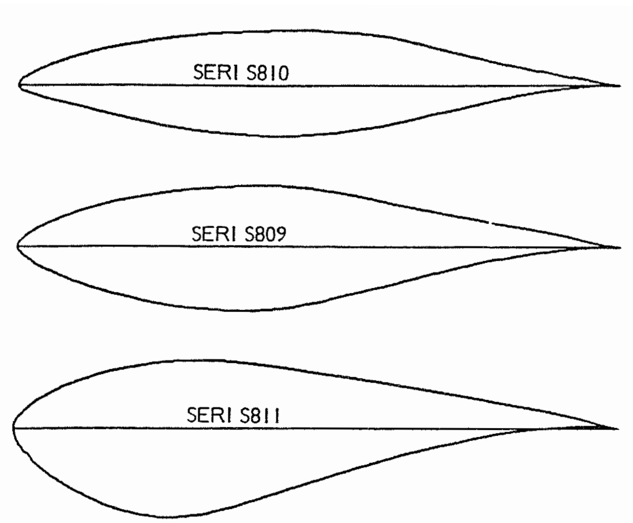

Figure 4. THE THICK AIRFOIL FAMILY (LOW $C_{l,max}$)

WIND-TUNNEL TESTS (TWO-DIMENSIONAL)

Wind-tunnel tests were conducted, at Delft University in the Netherlands, for the primary airfoils of the thin and thick families that have a low $C_{l,max}$ over the outboard portion of the blade. The first of these performance-verification tests, for the S805, was conducted in May 1985. The second test, for the S809, was conducted in October 1986. The test results provided a calibration of the Eppler airfoil design code that now allows other new airfoils to be designed with a high degree of confidence in their predicted performance characteristics. Consequently, wind-tunnel tests of each newly designed airfoil are not considered necessary to verify its predicted performance characteristics.

For the primary member of the thin airfoil family (the S805), a comparison of theoretical and experimental results is shown in Figure 5 for a smooth surface at a Reynolds number of 1×10^6. For C_l, predicted and measured results show good agreement up to an angle of attack of 6°. From that point, the slopes of both curves decrease because of the onset of trailing-edge separation. Although the Eppler code does a good job of predicting the onset of separation, it underestimates the degree of slope change prior to stall. (Stall occurs when

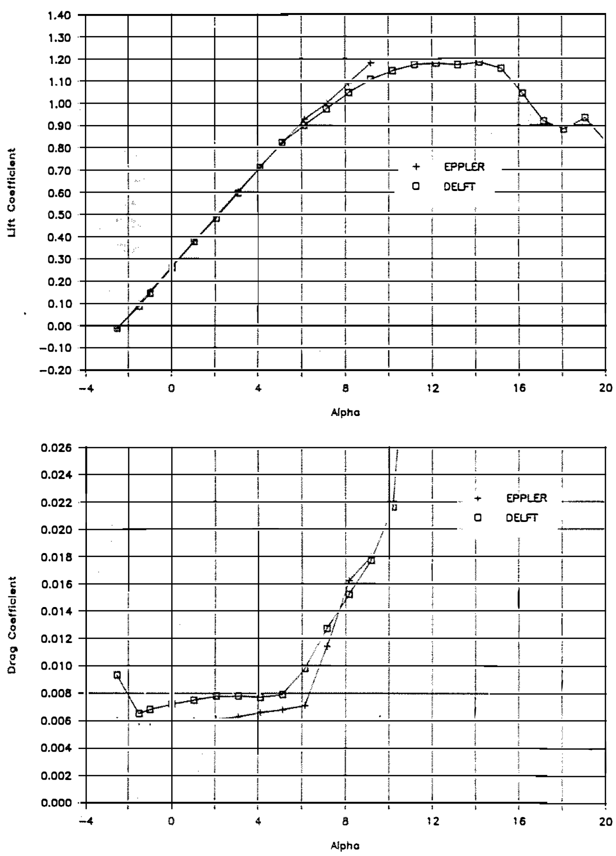

Figure 5. **THE S805 AIRFOIL'S PREDICTED (EPPLER) AND MEASURED (DELFT) PERFORMANCE CHARACTERISTICS**

the predicted trailing-edge separation exceeds 10% of the chord or C_d exceeds 0.024.) Thus, the predicted $C_{l,max}$ of slightly less than 1.2 is in close agreement with the measured value. Measured poststall characteristics of the S805 are seen to be mild, with the $C_{l,max}$ remaining constant over a wide range of angles of attack. For the rough surface condition, the measured $C_{l,max}$ data for the S805 showed no significant change.

The comparison of C_d shows significant differences between predicted and measured values. Measured drag was found to be substantially higher than predicted, with the largest difference occurring in the middle of the drag bucket. This bump indicates the presence of strong laminar separation bubbles on the upper and/or lower surface. In the middle of the bucket, the drag associated with the upper and lower surface bubbles is at a maximum. As the angle of attack increases from this point, the upper surface separation bubble decreases in intensity as it moves forward, resulting in a smaller discrepancy between predicted and measured results. However, in this case, most of the discrepancy still exists; this indicates that the lower surface separation bubble is more significant than is the upper surface bubble and results in the largest part of the discrepancy between predicted and measured drag. These differences in the drag curves were unexpected and indicted that the Eppler airfoil design code underpredicted the significance of the laminar separation bubbles at a Reynolds number of 1×10^6. Excellent agreement between predicted and measured drag was found at a Reynolds number of 2×10^6. This agreement is attributed to the disappearance of the laminar separation bubbles as Reynolds number increased. These results indicate that the S805, as well as the S806, is suited for 20-m-diameter rotors (as characterized by a Reynolds number in the 2×10^6 range). Subtle geometric changes were made to the airfoils to provide a more favorable upper and lower surface pressure recovery and minimize the intensity of the laminar separation bubbles at a Reynolds number of 1×10^6. The resulting S805A and S806A airfoils now satisfy the needs of the 10-m-diameter rotor.

For the primary airfoil (S809) of the thick airfoil family, a comparison between predicted and measured performance is shown in Figure 6 for a smooth surface at a Reynolds number of 2×10^6. For C_l, excellent agreement is seen over the whole range of angle of attack. The measured $C_{l,max}$ agrees with the design value of 1.0 and occurs at an angle of attack of 9°. The poststall characteristics of this airfoil are very unusual in that $C_{l,max}$ stays between 1.0 and 1.1 up to an angle of attack of 17°. Again, as with the S805, the surface roughness was found to have little effect on the airfoil's $C_{l,max}$ and poststall C_l.

A comparison of the predicted and measured C_d shows good agreement over the whole range of angle of attack. The flatness of the measured drag bucket indicates that no significant laminar separation bubbles are present on the airfoil. Adding roughness to the S809 increased the $C_{d,min}$ about 60% over the drag bucket. The higher value is about equivalent to the minimum drag of a turbulent-flow airfoil of this thickness.

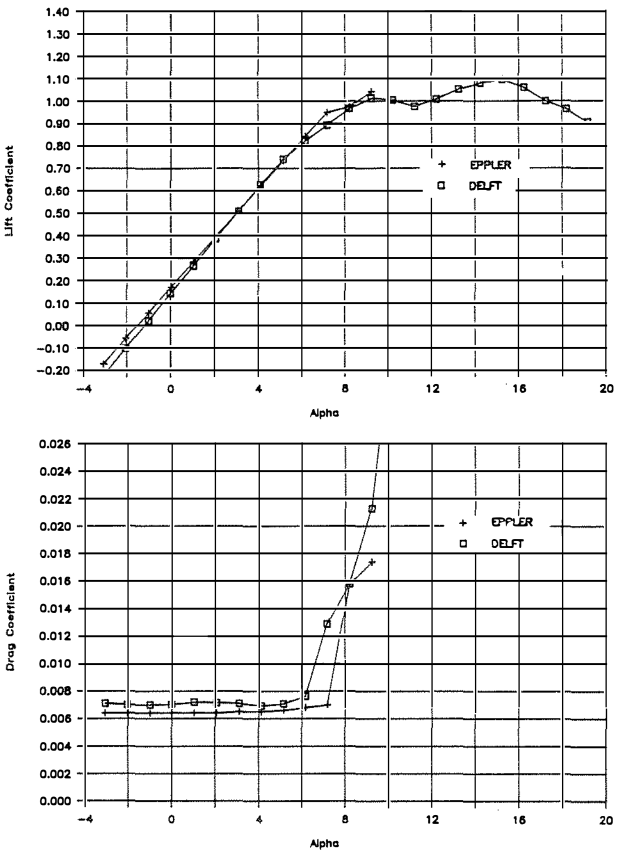

Figure 6. THE S809 AIRFOIL'S PREDICTED AND MEASURED PERFORMANCE CHARACTERISTICS

ATMOSPHERIC TESTING SPONSORED BY DOE/SERI

Atmospheric testing of the special-purpose airfoil families will determine to what degree these new airfoils satisfy the design objectives. Through a competitive procurement, two contracts were awarded in early 1987 to atmospherically test the thin airfoil family (805A, 806A, 807) on two different rotor systems (see Figure 7) in the 10-m-diameter range. One of these systems is a Carter 25 wind turbine with a two-bladed teetering rotor. The other rotor is a three-bladed (Phoenix) retrofit rotor designed by WestWind Industries to replace the inoperable GE-3 two-bladed flex-beam rotor system.

For the Carter 25, the comparison of the thin airfoil family will be relative to baseline blades having the NACA 23XXX airfoils. For the WestWind Phoenix, the baseline rotor will have 6-m Aerostar blades that use the NACA 44XX airfoils.

To provide a fair comparison, each of the two test rotors (with the new airfoils) will operate beside a similar baseline machine. To minimize the number of variables, the blades with the thin airfoil family are expected to have dynamic characteristics and an airfoil-thickness distribution close to those of the baseline blades. During the side-

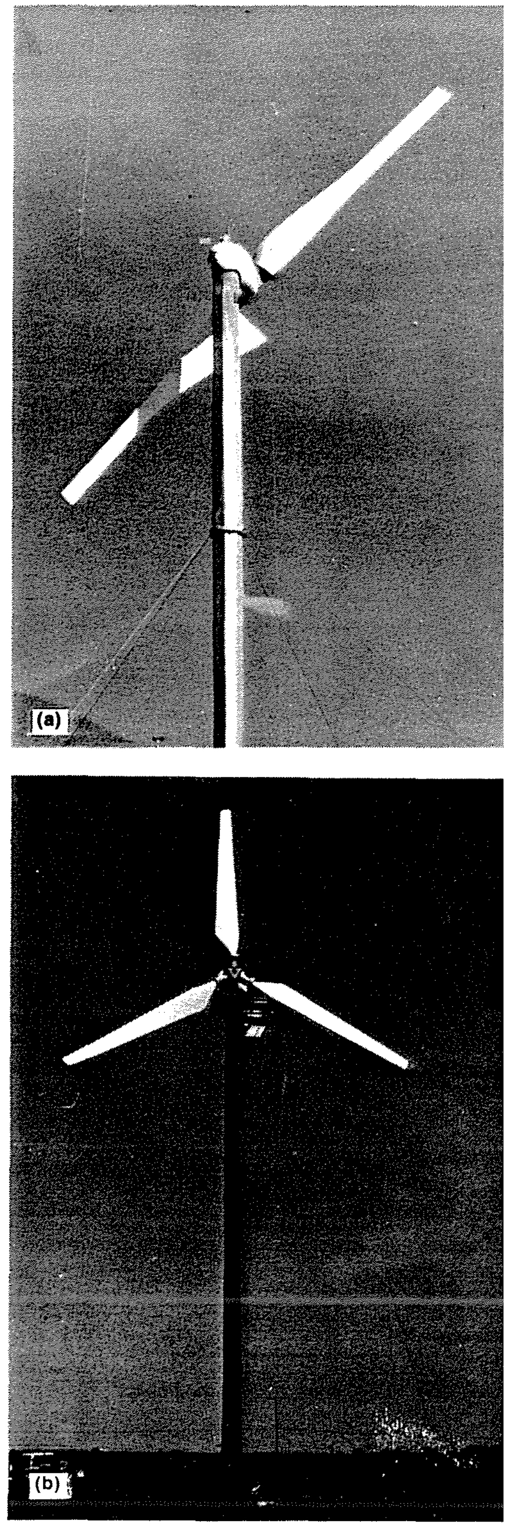

Figure 7. **ATMOSPHERIC TESTS OF THE THIN AIRFOIL FAMILIES.** (A) CARTER 25, DIA. = 9.9 m, (B) WESTWIND PHOENIX, DIA. = 12.5 m

by-side comparison, rotor performance curves and comparisons of annual energy output are to be established for both smooth and rough surfaces. Blade root bending moments will be monitored to help determine the effectiveness of the new airfoils in reducing blade fatigue loads. Noise measurements are planned to quantify any changes in the aerodynamic noise levels. Test data for the comparisons should be available by mid-1988.

In late 1987, DOE/SERI released a request for proposal for the thick-airfoil atmospheric test. This airfoil family (S812, S813, S811) is to be tested on a rotor system in the 20-m-diameter range. One or two contracts will be awarded in early 1988. The comparisons will likely be similar to those of the thin airfoil family. Actual test data from the thick-airfoil comparison are expected to be available in early 1989.

CONCLUSIONS

Three airfoil families have been developed for horizontal-axis wind turbines. A primary design requirement for all three families was that the airfoils operating over the outboard portion of the blade have a $C_{l,max}$ that is relatively insensitive to leading-edge roughness effects for consistent peak power output. The most distinguishing difference between the airfoil families is that the thin airfoil family with a high $C_{l,max}$ outboard is best suited for wind sites having high mean annual wind speeds, whereas the thin airfoil family with a low $C_{l,max}$ outboard is best suited for wind sites having mean annual wind speeds in the range of 5.4-6.3 m/s (12-14 mph). Similarly, the thick airfoil family is suited for the latter sites but addresses the more demanding structural requirements of composite wood blades and large rotors. Final verification of the design objectives for the thin and thick airfoil families will be through atmospheric tests conducted in 1988 and 1989.

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