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NREL Airfoil Families for HAWTs

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ABSTRACT

The development of special-purpose airfoils for horizontal-axis wind turbines (HAWTs) began in 1984 as a joint effort between the National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute (SERI), and Airfoils, Incorporated. Since that time seven airfoil families have been designed for various size rotors using the Eppler Airfoil Design and Analysis Code. A general performance requirement of the new airfoil families is that they exhibit a maximum lift coefficient ($c_{l,max}$) which is relatively insensitive to roughness effects. The airfoil families address the needs of stall-regulated, variable-pitch, and variable-rpm wind turbines. For stall-regulated rotors, better peak-power control is achieved through the design of tip airfoils that restrain the maximum lift coefficient. Restrained maximum lift coefficient allows the use of more swept disc area for a given generator size. Also, for stall-regulated rotors, tip airfoils with high thickness are used to accommodate overspeed control devices. For variable-pitch and variable-rpm rotors, tip airfoils having a high maximum lift coefficient lend themselves to lightweight blades with low solidity. Tip airfoils having low thickness result in less drag for blades having full-span pitch control. Annual energy improvements from the NREL airfoil families are projected to be 23% to 35% for stall-regulated turbines, 8% to 20% for variable-pitch turbines, and 8% to 10% for variable-rpm turbines. The improvement for stall-regulated turbines has been verified in field tests.

INTRODUCTION

Over the past decade, commonly used airfoil families for horizontal axis wind turbines (HAWTs) have included the NACA 44XX, NACA 23XXX, NACA 63XXX, and NASA LS(1) series airfoils. All these airfoils suffer noticeable performance degradation from roughness effects resulting from leading-edge contamination. Annual energy losses due to leading-edge roughness are greatest for stall-regulated rotors. The loss is largely proportional to the reduction in maximum lift coefficient ($c_{l,max}$) along the blade. High blade-root twist helps reduce the loss by keeping the blade's angle-of-attack distribution away from stall which delays the onset of $c_{l,max}$. Roughness also degrades the airfoil's lift-curve slope and increases the profile drag which contributes to further losses. For stall-

regulated rotors, whose angle of attack distribution increases with wind speed, the annual energy loss is typically 20% to 30%. Variable-pitch toward stall would result in similar roughness losses as fixed-pitch, stall-regulation, while variable-pitch toward feather would decrease the loss to around 10% at the expense of the rotor being susceptible to power spikes in turbulent high winds. For variable-rpm rotors operating at constant tip-speed ratio and angle of attack distribution, the loss is minimal at around 5% to 10%. To minimize the energy losses due to roughness effects and to develop special-purpose airfoils for HAWTs, the National Renewable Energy Laboratory (NREL), formerly the Solar Energy Research Institute (SERI), and Airfoils Inc. began a joint airfoil development effort in 1984. Results of this effort are reported in References 1 and 2. Estimated annual energy improvements and the component improvements from the NREL airfoils for stall-regulated, variable-pitch, and variable-rpm rotors are shown in Table 1.

Table 1. Estimated Annual Energy Improvements from NREL Airfoil Families

Turbine Type	Roughness Insensitive $c_{l,max}$	Correct Reynolds Number	Low Tip $c_{l,max}$	Total Improvement
Stall-Regulated	10% to 15%	3% to 5%	10% to 15%	23% to 35%
Variable-Pitch	5% to 15%	3% to 5%	---	8% to 20%
Variable-RPM	5%	3% to 5%	---	8% to 10%

By using the NREL airfoils, which are specifically designed for HAWTs, the annual energy production loss due to airfoil roughness effects can be cut in half relative to previously used aircraft airfoils. Optimizing an airfoil's performance characteristics for the appropriate Reynolds number and thickness provides additional performance enhancement in the range of 3% to 5%. Aircraft airfoils used on wind-turbine blades are often used at a lower Reynolds number than that intended by their designers. In addition, the airfoils are often scaled to a greater thickness which often leads to undesirable performance characteristics. The performance characteristics of the NACA 23XXX series of airfoils, for example, deteriorate quite rapidly with increasing airfoil thickness. This problem is further compounded in the blade root area by combining a low Reynolds number with high thickness. Such a combination makes it difficult to achieve good airfoil performance characteristics. For stall-regulated rotors, further performance enhancement is achieved by using blade tip airfoils with low $c_{l,max}$ which helps control peak rotor power. This allows the use of 10% to 15% more swept rotor area for a given generator size.

Desirable performance characteristics for wind-turbine airfoils depend on whether the machine is stall-regulated, variable-pitch, or variable-rpm. For stall-regulated machines, restrained maximum lift coefficient in the blade tip region is desired to passively control peak rotor power. This feature will also benefit machines with variable-pitch blades that pitch toward stall to control peak power, such as the NedWind 500 kW. Variable pitch machines that pitch toward feather to control peak power have the option of using tip airfoils with either high or low maximum lift coefficient depending on whether the machine is designed to operate at high or low rpm. However, pitching toward feather results in excessive turbulence-induced peak-power spikes (Reference 3) that create operation and

maintenance problems. Power spikes are effectively eliminated through variable-rotor-rpm operation which absorbs the power spikes with an increase in rpm.

The seven NREL airfoil families, which include over twenty different airfoils, have been designed using the Eppler code (References 4 and 5) to accommodate the unique operating requirements of stall-regulated, variable-pitch, and variable-rpm wind turbines. Most of the existing NREL airfoil families address the needs of stall-regulated wind turbines. Efforts currently underway are focusing on tip airfoils for variable-rpm wind turbines. This paper provides a summary of the existing NREL airfoil families and those currently being designed.

NREL AIRFOIL FAMILIES

Seven airfoil families consisting of 23 airfoils have been designed for various size rotors since 1984. The appropriate blade length and generator size for each airfoil family along with the corresponding airfoils comprising each family from blade root to tip are shown in Table 2. The airfoil designations starting with the S801 and ending with the S823 represent the numerical order in which the airfoils were designed between 1984 and 1993. The "A" designation stands for an improved version of an airfoil based on wind-tunnel test results for a similar airfoil. The three airfoils having underlined bold lettering have undergone comprehensive tests in the Delft University low-turbulence wind tunnel. Test results for these three airfoils are covered in References 6, 7, and 8. Five of the airfoil families are designated "thick" (16% to 21%) to indicate that the tip-region airfoils are thick enough to accommodate overspeed-control aerodynamic devices and to reduce the blade weight. These "thick" airfoil families lend themselves to stall-regulated wind turbines. The two airfoil families labeled "thin" (11% to 15%) are more suited to variable-pitch or variable-rpm turbines that use full-span blade pitch. Greater thickness is desired for the blade-root airfoils to accommodate structural and dynamic considerations. The blade-root airfoil thickness falls in the range of 18% to 24%. Thicknesses greater than 26% were found to result in unacceptable performance characteristics.

Table 2. NREL Airfoil Families

Blade Length (meters)	Generator Size (kW)	Thickness Category	Airfoil Family (root-----tip)			
1-5	2-20	thick		S823		S822
5-10	20-150	thin		S804	S801	S803
5-10	20-150	thin	S808	S807	<u>S805A</u>	S806A
5-10	20-150	thick		S821	S819	S820
10-15	150-400	thick	S815	<u>S814</u>	<u>S809</u>	S810
10-15	150-400	thick	S815	<u>S814</u>	S812	S813
15-25	400-1000	thick		S818	S816	S817

All of the airfoils, with the exception of the early blade-root airfoils (S804, S807, S808 and S811), are designed to have a $c_{l,max}$ which is largely insensitive to roughness effects. This is accomplished by insuring that the transition from laminar to turbulent flow on the suction side of the airfoil occurs very near the leading edge just prior to reaching $c_{l,max}$. The airfoils achieve low drag in the clean condition through the achievement of extensive laminar flow. The tip-region airfoils typically have close to 50% laminar flow on the suction surface and over 60% laminar flow on the pressure surface. The moment coefficient for the airfoils is generally proportional to $c_{l,max}$. Consequently, the low $c_{l,max}$ tip-region airfoils exhibit lower moment coefficients than modern aft-cambered aircraft airfoils. The airfoils also have soft-stall characteristics which result from progressive trailing-edge separation. In turbulent wind conditions, close to peak power, soft stall helps mitigate power and load fluctuations resulting from local intermittent stall along the blade. The discussion of the individual airfoil families proceeds from small to large blades as listed in Table 2.

Blades 1 to 5 Meters in Length

One airfoil family (Fig. 1), which consists of a root airfoil (S823) and tip airfoil (S822), was designed in 1993 for small turbines rated at 2-20 kW. The design specifications for this family indicate a tip region $c_{l,max}$ of 1.0 and a minimum drag $C_{d,min}$ of 0.010 for a Reynolds number of 600,000. The very low Reynolds number range for this family contributes to a higher $c_{d,min}$ and increased difficulty in achieving a high root airfoil $c_{l,max}$ (1.2) for a Reynolds number of 400,000. This airfoil family is suitable for many small variable-rpm machines such as the Jacobs 17.5 kW machine.

Blades 5 to 10 Meters in Length

Three airfoil families (Figs. 2,3, and 4) have been designed for medium size turbines rated at 20-100 kW. The first family, with thin tip airfoils, was designed in 1984 and includes the S801, S803, and S804 airfoils. This family has tip airfoils with a high design $c_{l,max}$ (1.6). The airfoil family may be suitable for variable-rpm and variable-pitch (to feather) turbines having low blade solidity. Efforts are currently underway to design a high $c_{l,max}$ airfoil family for 10- to 20-meter blades using improved techniques which have been developed as a result of the three Delft wind-tunnel tests conducted since the design of the first family. The second family, also with thin tip airfoils, was designed in 1984 and includes the S805, S806, S807, and S808 airfoils. This airfoil family was designed to have a low tip $c_{l,max}$ (1.0) for a Reynolds number just over 1,000,000. The airfoil family is suitable for stall-regulated blades and is used on the Phoenix Industries 7.9-meter retrofit blade. Over 90 sets of these blades are operating on 65-80 kW wind turbines in the California wind parks (Reference 1). Improved versions (S805A and S806A) of the tip-region airfoils in this family were designed in 1987 based on the wind-tunnel results obtained for the S805 airfoil in 1985. The third family, having thick tip airfoils, was designed in 1993 and consists of the S819, S820, and S821 airfoils. This family was designed to have performance characteristics similar to the preceding family. The greater tip-region thickness helps accommodate overspeed-control mechanisms for stall-regulated rotors at the expense of slightly higher drag. The S821 blade-root airfoil was designed to have a high $c_{l,max}$ which is largely insensitive to roughness effects. Insensitivity to roughness was not a design requirement for the root airfoils (S804, S807, and S808) of the preceding two airfoil families in this category.

Blades 10 to 15 Meters in Length

Two airfoil families (Figs. 5 and 6) have been designed for large rotors rated at 100-400 kW. The families share common root airfoils. The first family was designed in 1986 and included the S809, S810, and S811. The S811 root airfoil, which was not designed for insensitivity to roughness, was replaced in 1991 by the S814 and S815. These airfoils have a $c_{l,max}$ that is largely insensitive to roughness effects. The S810 tip-region airfoil has a $c_{l,max}$ (0.9) which is the lowest value of all the NREL airfoils. The lower $c_{l,max}$ allows the use of a longer blade for a given peak power which provides greater swept disc area for low wind speed sites. This airfoil family is used on the AWT 300 kW two-bladed machine. The second family was designed in 1988 and includes the S812 and S813 outboard airfoils which are also used with the more recent S814 and S815 root airfoils. The S813 tip-region airfoil has a slightly higher $c_{l,max}$ (1.1) and slightly less thickness at 16%. This airfoil family is being used successfully on the AOC 15/50 three-bladed wind turbine. A set of high $c_{l,max}$ tip airfoils (S825 and S826) is currently being designed to be used with the S814 and S815 root airfoils. This new airfoil family under development will focus on variable-rpm rotors that use lightweight, low solidity blades.

Blades 15 to 25 Meters in Length

One airfoil family (Fig. 7) was designed in 1992 for extra-large blades for turbines rated at 400-1000 kW. This family, which lends itself to stall-regulated rotors, includes the S816, S817, and S818 airfoils. The tip-region airfoil has a $C_{l,max}$ of 1.1 and a thickness of 16%. This airfoil family is used on the new Zond 500 kW three-bladed wind turbine. Another set of airfoils (S827 and S828) is being designed for this family with tip-region airfoil $c_{l,max}$ of 0.9. This set of airfoils will allow the use of more swept area for a given generator size.

CONCLUSIONS

Over the past ten years, 23 airfoils that comprise seven airfoil families have been designed to address the unique performance characteristics of HAWTs. Three of these airfoils have undergone extensive testing in the Delft low-turbulence wind tunnel to verify their predicted performance characteristics and to better calibrate the Eppler Airfoil Design and Analysis Code. Four of the airfoil families are being successfully used on commercial wind-turbine blades. These blades are providing large increases in annual energy production as a result of less sensitivity to roughness effects, better lift-to-drag ratios, and, in the case of stall-regulated rotors, through the use of more swept area for a given generator size. Because of the economic benefits provided by these airfoils, they are expected to be the airfoils of choice for retrofit blades and most new domestic wind turbines.

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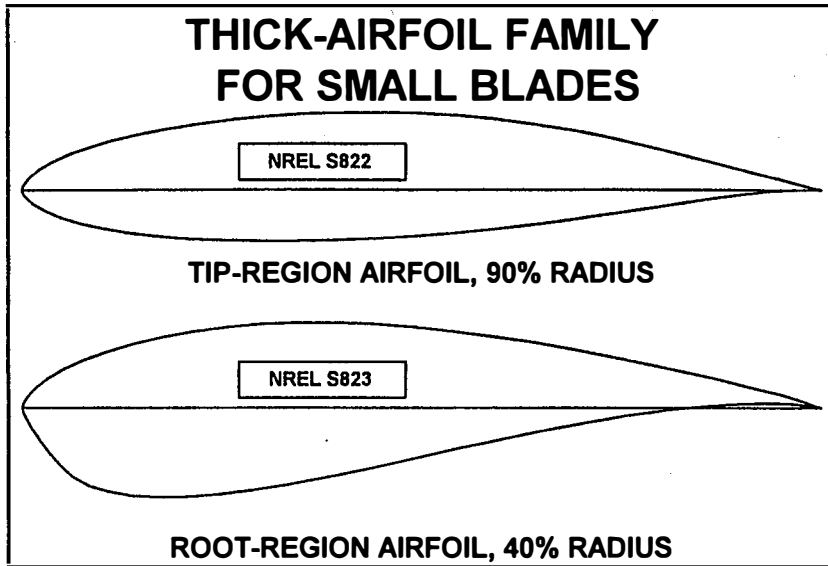
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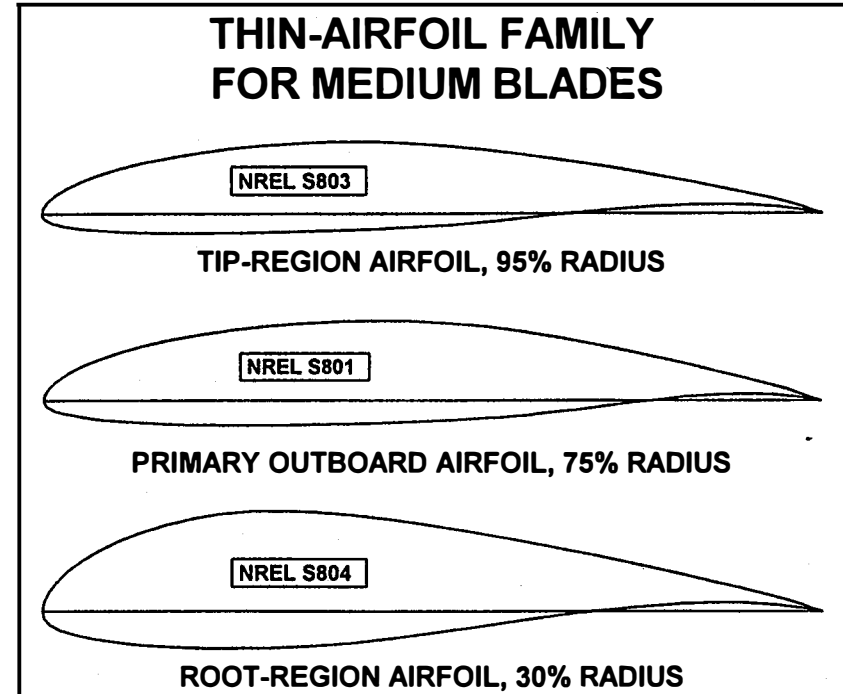
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Design Specifications

Airfoil	r/R	Re. No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S822	0.90	0.6	0.160	1.0	0.010	-0.07
S823	0.40	0.4	0.210	1.2	0.018	-0.15

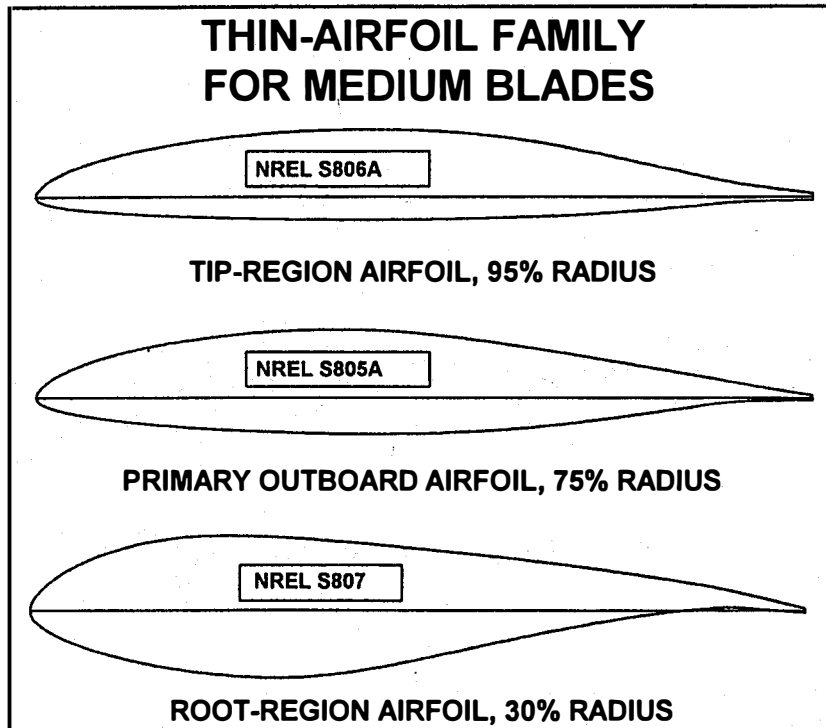


Design Specifications

Airfoil	r/R	Re. No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S803	0.95	2.6	0.115	1.5	0.006	-0.15
S801	0.75	2.0	0.135	1.5	0.007	-0.15
S804	0.30	0.8	0.180	1.5	0.012	-0.15

Fig. 1. Thick-Airfoil Family for Small Blades (low tip $c_{l,max}$).

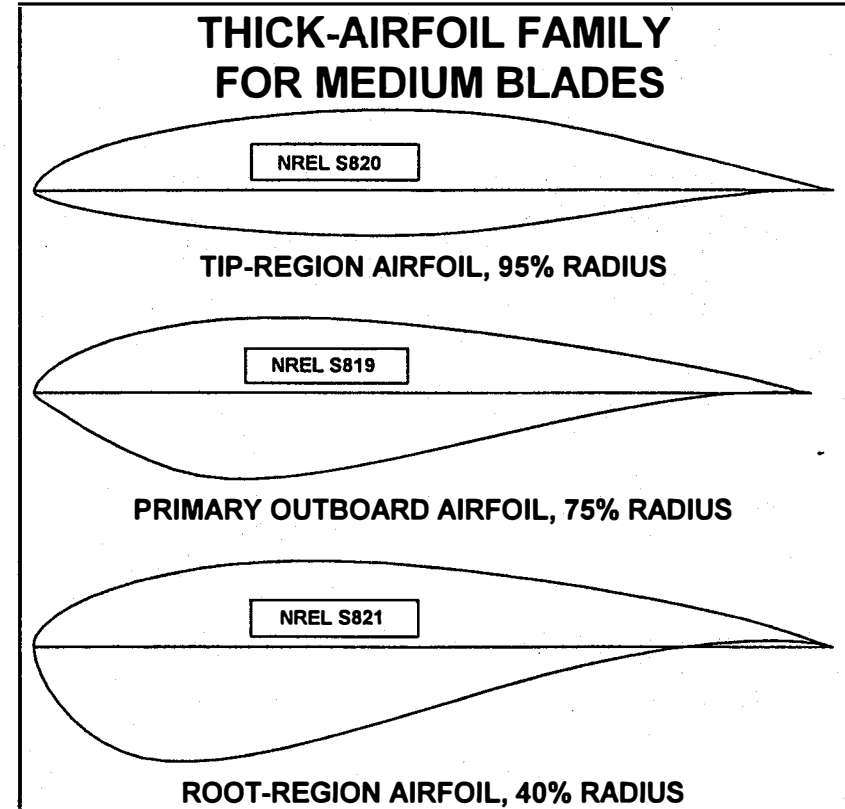
Fig. 2. Thin-Airfoil Family for Medium Blades (high tip $c_{l,max}$).



Design Specifications

Airfoil	r/R	Re. No. ($\times 10^6$)	t/c	c_{lmax}	c_{dmin}	c_{mo}
S806A	0.95	1.3	0.115	1.1	0.004	-0.05
S805A	0.75	1.0	0.135	1.2	0.005	-0.05
S807	0.30	0.8	0.180	1.4	0.010	-0.10
S808	0.20	0.4	0.210	1.2	0.012	-0.12

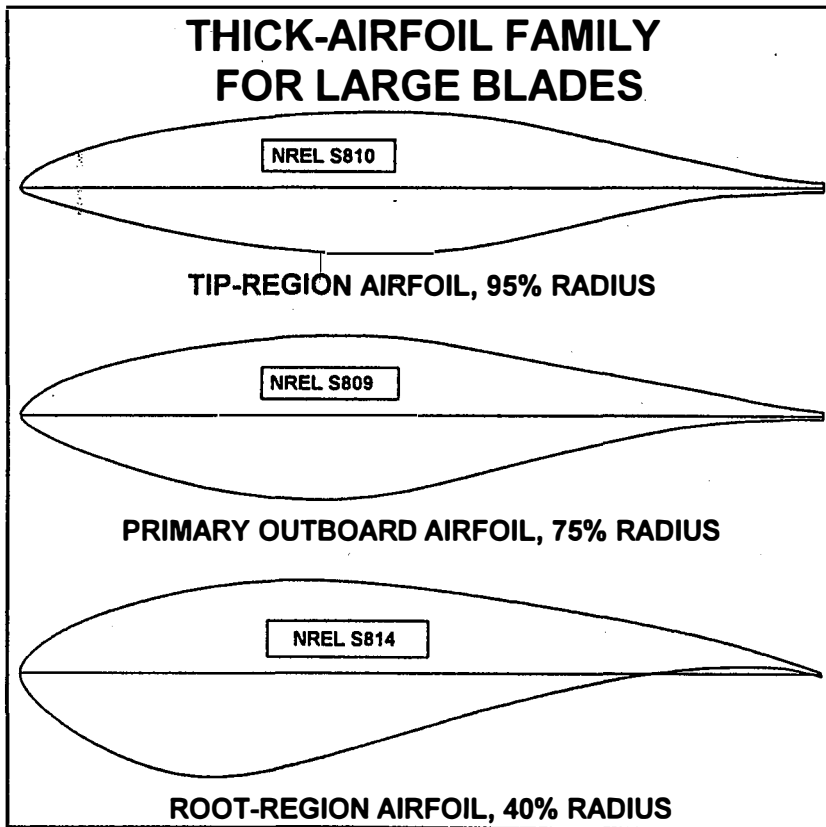
Fig. 3. Thin-Airfoil Family for Medium Blades (low tip $c_{l,max}$).



Design Specifications

Airfoil	r/R	Re. No. ($\times 10^6$)	t/c	c_{lmax}	c_{dmin}	c_{mo}
S820	0.95	1.3	0.160	1.1	0.007	-0.07
S819	0.75	1.0	0.210	1.2	0.008	-0.07
S821	0.40	0.8	0.240	1.4	0.014	-0.15

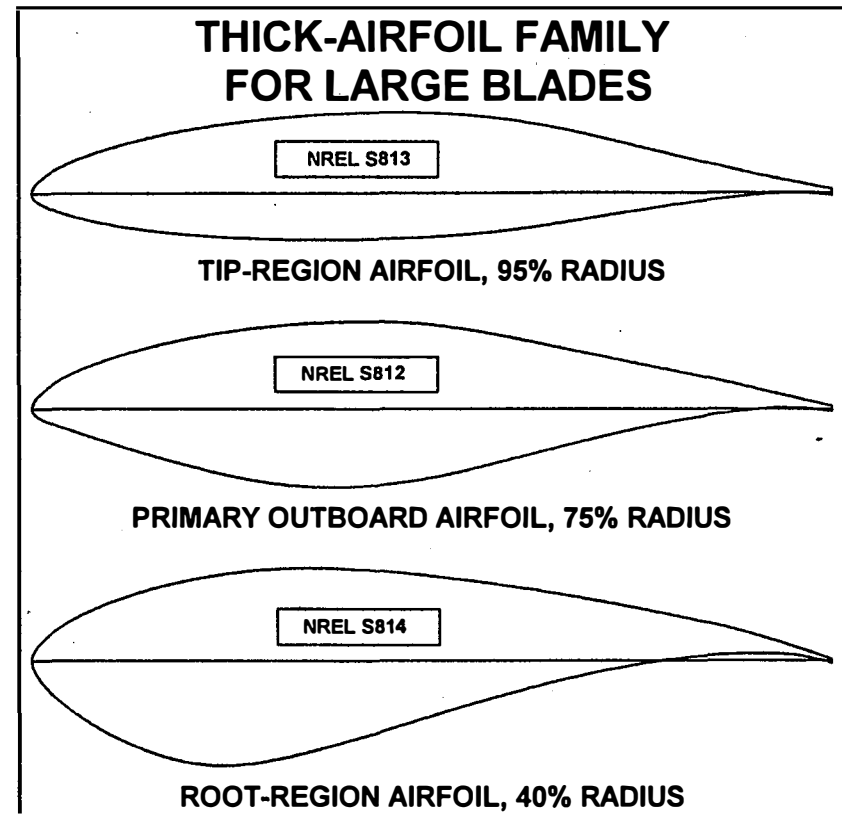
Fig. 4. Thick-Airfoil Family for Medium Blades (low tip $c_{l,max}$).



Design Specifications

Airfoil	r/R	Re. No. (x10 ⁶)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S810	0.95	2.0	0.180	0.9	0.006	-0.05
S809	0.75	2.0	0.210	1.0	0.007	-0.05
S814	0.40	1.5	0.240	1.3	0.012	-0.15
S815	0.30	1.2	0.260	1.1	0.014	-0.15

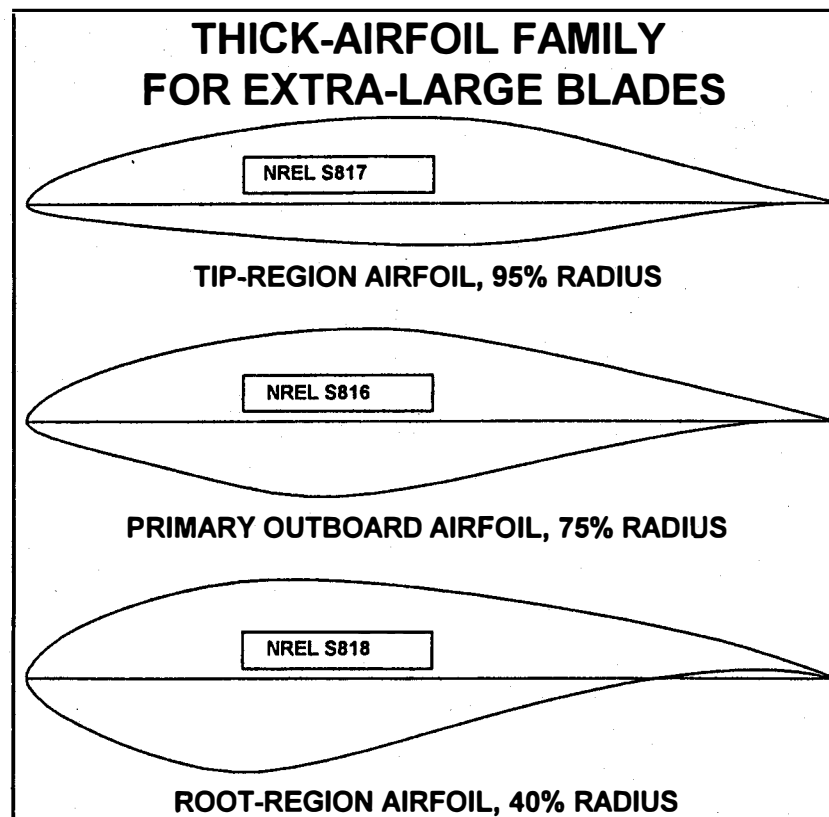
Fig. 5. Thick-Airfoil Family for Large Blades (lower tip $C_{l,max}$).



Design Specifications

Airfoil	r/R	Re. No. (x10 ⁶)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S813	0.95	2.0	0.160	1.1	0.007	-0.07
S812	0.75	2.0	0.210	1.2	0.008	-0.07
S814	0.40	1.5	0.240	1.3	0.012	-0.15
S815	0.30	1.2	0.260	1.1	0.014	-0.15

Fig. 6. Thick-Airfoil Family for Large Blades (low tip $C_{l,max}$).



Design Specifications

Airfoil	r/R	Re. No. ($\times 10^6$)	t/c	$C_{l,max}$	$C_{d,min}$	C_{mo}
S817	0.95	3.0	0.160	1.1	0.007	-0.07
S816	0.75	4.0	0.210	1.2	0.008	-0.07
S818	0.40	2.5	0.240	1.3	0.012	-0.15

Fig. 7. Thick-Airfoil Family for Extra-Large Blades (low tip $c_{l,max}$).