# 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 nine 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 outboard 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, thicker tip airfoils help accommodate overspeed control devices. For variable-pitch and variable-rpm rotors, outboard airfoils having a high maximum lift coefficient lend themselves to lower blade solidity. Airfoils having greater thickness result in greater blade stiffness and tower clearance. Airfoils of low thickness result in less drag and are better suited for downwind machines. 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 can be 20% to 30% where leading edge contamination from insects and airborne pollutants is common. 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 normally makes it difficult to achieve good airfoil performance characteristics. For stall-regulated rotors, further performance enhancement is achieved by using blade outboard 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 outboard blade 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 the desired rotor solidity and 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 NREL airfoil families 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. Many of the existing NREL airfoil families address the needs of stall-regulated wind turbines. However, recent efforts have focused on outboard airfoils for variable-rpm wind turbines. This paper provides a summary of the NREL airfoil families.

## NREL AIRFOIL FAMILIES

Nine airfoil families consisting of 25 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 S828 represent the numerical order in which the airfoils were designed between 1984 and 1995. 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. Seven of the airfoil families are designated "thick" which indicates that the outer-blade airfoils are 16% to 21% thick. Greater thickness helps provide greater blade flap stiffness for tower clearance, lower blade weight important for large machines, and helps accommodate aerodynamic overspeed control devices for stall-regulated machines. The two airfoil families labeled "thin" (11% to 15%) are more suited to downwind rotors of small to medium blade length. For most all blades, very thick airfoils are desired for the blade-root 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 undesirable performance characteristics.

Table **2. NREL Airfoil Families**

| **Blade Length (meters)** | **Generator (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 | **S805**A | S806A |
| 5-10 | 20-150 | thick | | S821 | S819 | S820 |
| 10-15 | 150-400 | thick | S815 | **S814** | **S809** | S810 |
| 10-15 | 150-400 | thick | S815 | **S814** | S812 | S813 |
| 10-15 | 150-400 | thick | S815 | **S814** | S825# | S826# |
| 15-25 | 400-1000 | thick | | S818 | S816 | S817 |
| 15-25 | 400-1000 | thick | | S818 | S827 | S828 |

shaded - - - - - Ohio State, Univ. of Ill.
bold numbers - - - Delft tested
crosshatch - - - - - - high $c_{l,max}$ tip airfoils, S825 LTPT test

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 designed to have soft-stall characteristics, which result from progressive separation from the trailing-edge. In turbulent wind conditions, close to peak power, soft stall should help 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 thick airfoil family is suitable for small constant and variable-rpm machines such as the Jacobs 17.5 kW machine. For small turbines, blade deflection into the tower under high yaw rates and flutter must be avoided. Consequently, the high flap and torsion stiffness required dictate that the S822 tip airfoil have a thickness of 16%.

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. The second family, also with thin tip airfoils, was designed in 1984 and includes the S805A, S806A, 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 was 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). Based on the results of a 1985 wind-tunnel test of the S805, both the S805 and S806 outboard airfoils were redesigned and replaced by the better performing S805A and S806A airfoils. 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 and is used on the Northwind 100 kW turbine and for replacement blades on the USW 56/100. The greater tip-region thickness helps accommodate overspeed-control mechanisms for stall-regulated rotors and provides greater stiffness 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. For the two preceding airfoil families in this category, insensitivity to roughness was not a design requirement for their root airfoils (S804, S807, and S808).

Blades 10 to 15 Meters in Length

Three airfoil families (Figs. 5,6 and 7) 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 $c_{l,max}$ airfoils consisting of the outboard S825 airfoil and tip S826 airfoil were recently designed to also be used with the S814 and S815 root airfoils. This new airfoil family focuses on variable-rpm rotors that use highly tapered, low solidity blades. Performance of the S825 was verified in the NASA Langley Low Turbulence Pressure Tunnel (LTPT) for Reynolds numbers up to 6,000,000 (Reference 9).

Blades 15 to 25 Meters in Length

Two airfoil families (Fig.8 and 9) were designed in for extra-large blades for turbines rated at 400-1000 kW. These families lend themselves to stall-regulated rotors. The first family includes the S816, S817, and S818 airfoils. The outboard S816 airfoil has a design $c_{l,max}$ of 1.2 with a thickness of 21%and the tip-region S817 airfoil has a design $c_{l,max}$ of 1.1 with a thickness of 16%. This airfoil family provides outstanding performance on over 800 Zond 550 and 750 kW three-bladed wind turbines. The second family share the same S818 root airfoil but have a lower $c_{l,max}$ of 1.0 and 0.9 for the outboard S827 airfoil and tip-region S828 airfoil. This set of airfoils will allow the use of more swept area than the S816 and S817 airfoils for a given generator size.

## CONCLUSIONS

Nine airfoil families have been designed that comprise 25 airfoils 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. Five of the airfoil families are being successfully used on commercial wind-turbine blades. These blades are providing significant 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 recommended for retrofit blades and most new wind turbine designs.

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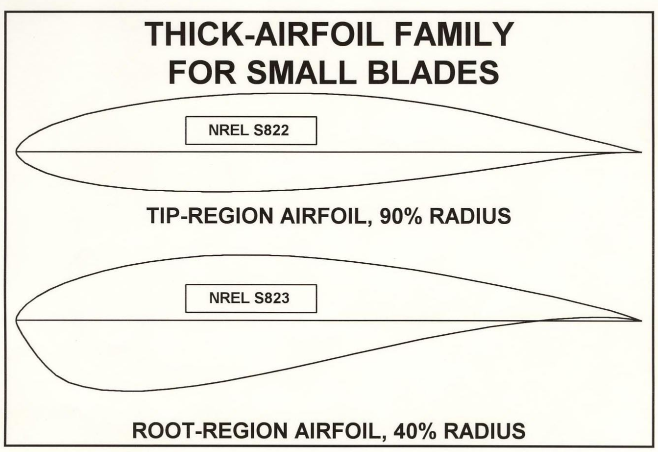
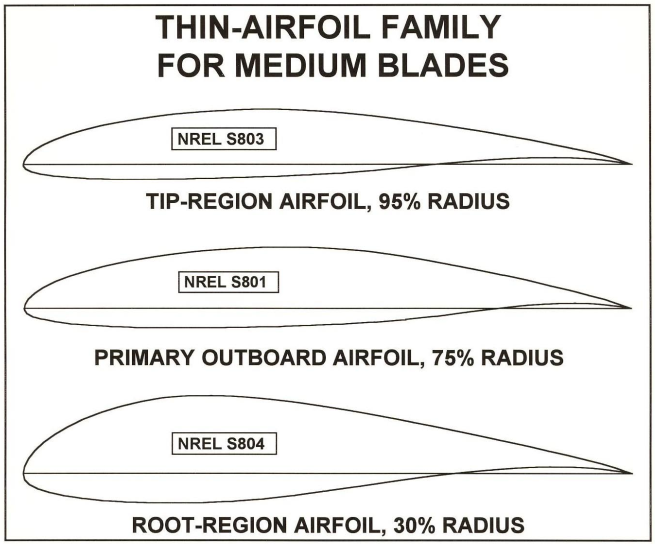



**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| 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 |

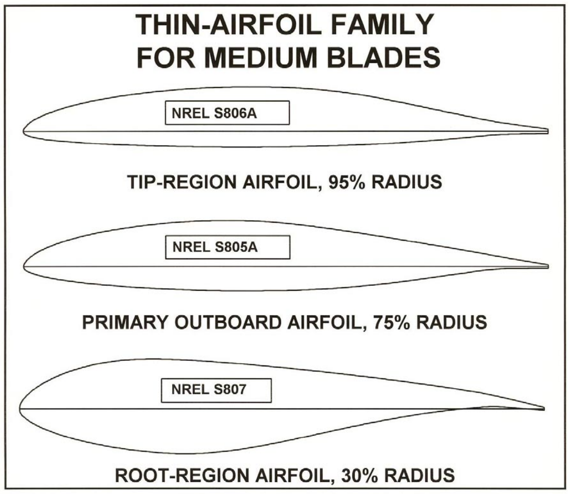
Fig. 1. Thick-Airfoil Family for Small Blades (low tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| 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 |

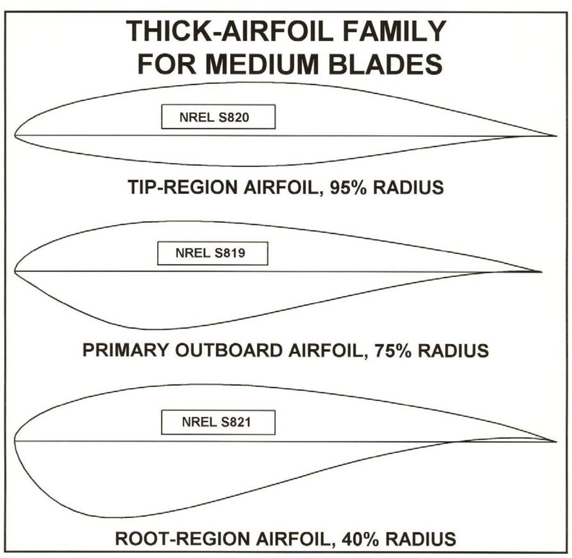
Fig. 2. Thin-Airfoil Family for Medium Blades (high tip $c_{l,max}$).




Design Specifications

| Airfoil | r/R | Re. No. ($x10^6$) | 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 |

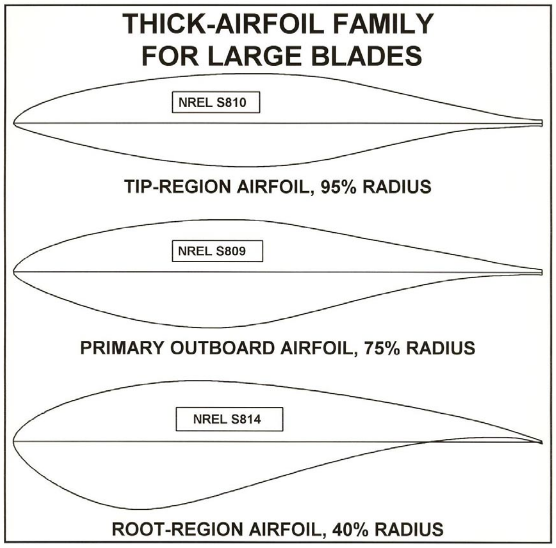
Fig. 3. Thin-Airfoil Family for Medium Blades (low tip $c_{l,max}$).




Design Specifications

| Airfoil | r/R | Re. No. ($x10^6$) | 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 |

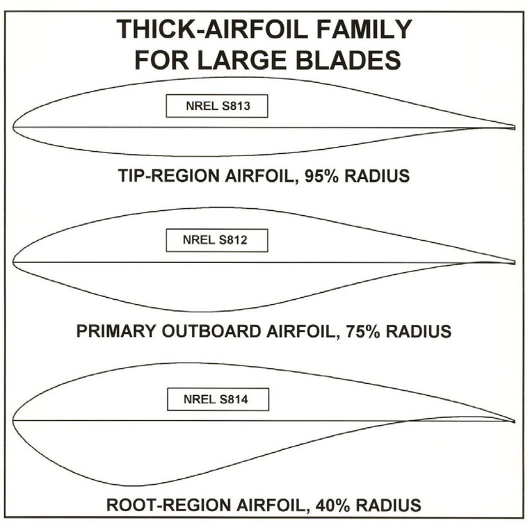
Fig. 4. Thick-Airfoil Family for Medium Blades (low tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| 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 |

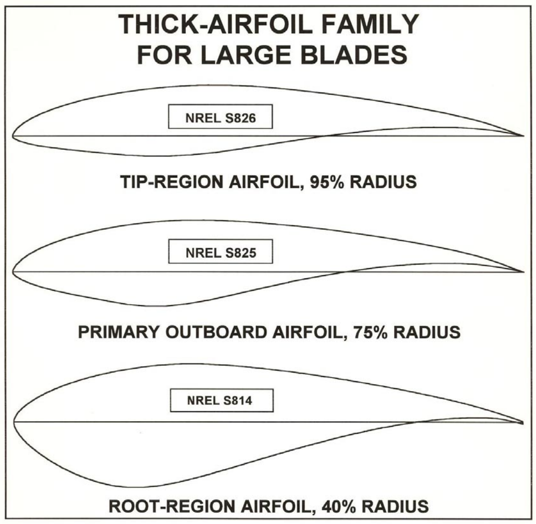
Fig. 5. Thick-Airfoil Family for Large Blades (lower tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| 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 |

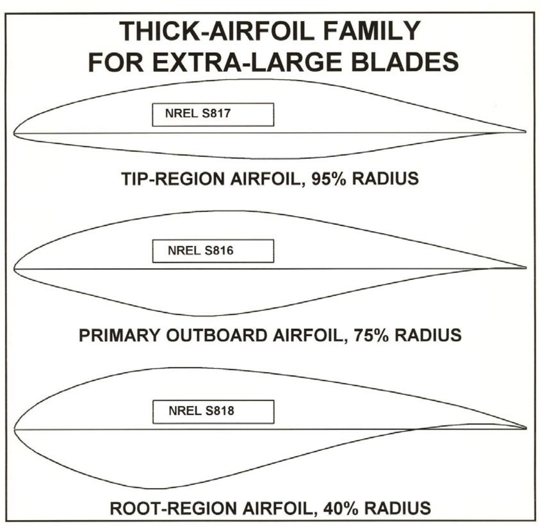
Fig. 6. Thick-Airfoil Family for Large Blades (low tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| S826 | 0.95 | 1.5 | 0.140 | 1.60 | 0.006 | -0.14 |
| S825 | 0.75 | 2.0 | 0.170 | 1.60 | 0.008 | -0.14 |
| S814 | 0.40 | 1.5 | 0.240 | 1.30 | 0.012 | -0.15 |
| S815 | 0.30 | 1.2 | 0.260 | 1.10 | 0.014 | -0.15 |

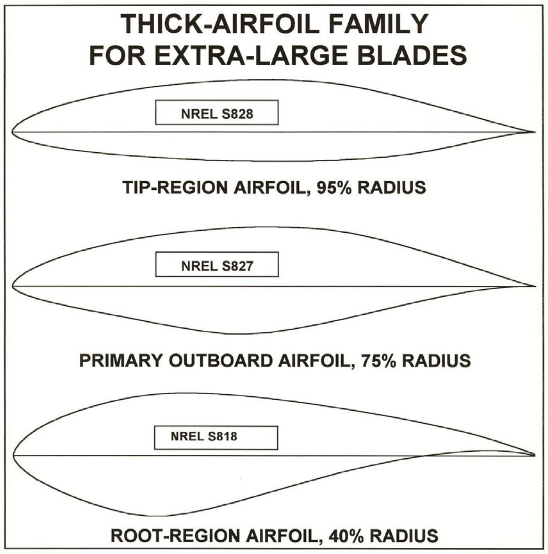
Fig. 7. Thick-Airfoil Family for Large Blades (high tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| 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. 8. Thick-Airfoil Family for Extra-Large Blades (low tip $c_{l,max}$).




**Design Specifications**

| Airfoil | r/R | Re. No. ($x10^6$) | t/c | $c_{lmax}$ | $c_{dmin}$ | $c_{mo}$ |
|---|---|---|---|---|---|---|
| S828 | 0.95 | 3.0 | 0.160 | 0.90 | 0.007 | -0.07 |
| S827 | 0.75 | 4.0 | 0.210 | 1.00 | 0.008 | -0.07 |
| S818 | 0.40 | 2.5 | 0.240 | 1.30 | 0.012 | -0.15 |

Fig. 9. Thick-Airfoil Family for Extra-Large Blades (lower tip $c_{l,max}$)