RECENT DARRIEUS VERTICAL AXIS WIND TURBINE AERODYNAMICAL EXPERIMENTS AT SANDIA NATIONAL LABORATORIES*

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ABSTRACT

Experiments contributing to the understanding of the aerodynamics of airfoils operating in the vertical axis wind turbine (VAWT) environment are described. These experiments are ultimately intended to reduce VAWT cost of energy and increase system reliability. They include chordwise pressure surveys, circumferential blade acceleration surveys, effects of blade camber, pitch and offset, blade blowing, and use of sections designed specifically for VAWT application.

INTRODUCTION

It is anticipated that reduction in cost of energy for VAWTs can be effected through relatively simple departures from the current aerodynamic design. This existing design uses blades of symmetrical cross-section mounted such that the radius from the tower centerline is normal to the blade chord at approximately the 40% chord point. The departures from this configuration are anticipated to 1) lower cut-in windspeed, 2) increase maximum aerodynamic efficiency, and 3) limit maximum aerodynamic output power. All of these effects have been shown to increase energy capture for a given basic system and/or reduce system cost for a given annual energy output.[1] The airfoil section characteristics which would bring about these departures are 1) lower section zero lift drag coefficient, C_{do}, 2) higher maximum section lift-to-drag ratio, $(\ell/d)_{max}$, and 3) lower section maximum lift coefficient, $C_{\ell max}$, and higher drag coefficient at which $C_{\ell max}$ occurs, respectively. Mounting the blade at some point radically different from the 40% chord point mentioned above would also alter operating characteristics. This will allow a torque due to the section normal force to contribute (either negatively or positively) to the rotor turning torque. This paper describes certain experiments designed to both better understand the aerodynamics of an airfoil section operating as a VAWT blade element and bring about some of the changes in section characteristics already noted. The common goal of all of these experiments is to lower VAWT cost of energy and increase system reliability.

EXPERIMENTS

There are currently six experimental programs either currently underway or planned for the near future using the Sandia 5-m and 17-m diameter, height-to-diameter of one, test bed turbines. These include blade chordwise pressure distribution and acceleration surveys, blade cambering, blade offset and preset pitch (incidence), blade blowing, and the use of blade sections designed to operate specifically in the VAWT environment.

Blade Chordwise Pressure Distribution Survey

The VAWT blade operating environment is a complicated one. A blade element follows a circular path through space over which both the velocity magnitude and direction are constantly changing. A blade element may stall and recover twice in a single revolution. A blade element sees a range of Reynolds numbers in a single revolution. Operation at very high angles of attack is common. Knowledge of how blade forces are produced under these circumstances is sparse. A program has been designed and hardware is being procured to measure blade transient surface pressures at various chordwise locations as functions of time. Taken concurrently with these pressures will be local flow angularity and local airspeed information. The former will be measured with 29 Entran Devices, Inc. EPF 200-10 semiconductor transducers distributed chordwise near the equatorial section of one 61 cm chord blade of the Sandia 17-m turbine, 18 on both the upper and lower surfaces of the NACA 0015 section and one at the leading edge. The flow angularity and speed will be measured with a 1.27 cm diameter circular cylinder hemispherically tipped probe extending 14 probe diameters ahead of the equatorial blade section. Blade position relative to a fixed compass point will be measured by an AST/Servo Systems, Inc. 23CX6 synchro. Ambient windspeed and direction will be taken from a directional anemometer mounted 7 m above the turbine rotor. The two directional readings will give blade position relative to the ambient wind at any given instant in time. Using time as a common parameter, chordwise pressure distributions along with local flow angularity and local flowspeed may be constructed as functions of tipspeed ratio and blade

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*This work supported by the U.S. Department of Energy under Contract No. DE-AC04-76DP00789.

circumferential location relative to ambient wind direction. It is expected that this detailed information will allow intelligent assessments of what is happening circumferentially locally in the generation of aerodynamic blade forces in the very complicated VAWT operating environment.

Blade Circumferential Acceleration Survey

An earlier 17-m experiment involved a limited circumferential survey of the blade equatorial section chordwise accelerations.[2] This information proved very valuable as it pointed out the existence of blade dynamic stall. It was noted that a more complete triaxial blade acceleration survey could be efficiently run simultaneously with the pressure survey described above. This survey will be taken using Schaevitz, Inc. LSMP1 (±1 g gravitational), LSMP2 (±2 g chordwise) and LSMP25 (±25 g normal) accelerometers. Accelerations will be measured as functions of time and related, as with the pressures, speeds and angularities, to tipspeed ratio and blade circumferential location relative to the ambient wind direction. These accelerations should prove helpful in evaluating the chordwise pressure data.

Blade Cambering

Blade section cambering has the potential for altering performance characteristics in two ways. The first one is to tailor section characteristics ($[\ell/d]_{max}$, $C_{\ell max}$, α_{stall}) to take advantage of the upwind-downwind and advancing-retreating rotor traverses. The upwind flowfield is relatively undisturbed and has the highest energy. The advancing portion of the trajectory has the highest relative airspeed. It may be possible to camber a blade element such that maximum efficiency is enhanced and a lower maximum power is achieved. The second idea is that a symmetrical blade section operating in a curvilinear flowfield acts like a cambered section, this being due to chordwise variations angle of attack stemming from the circular trajectory. The inverse of this concept is to add camber to any blade element (symmetrical or otherwise) such that the additional camber conforms to the trajectory of a point at the perpendicular intersection of a radial line from the axis of rotation to the element chord. This is postulated to reduce C_{do} and therefore decrease cut-in windspeed.

These two ideas are essentially independent but are both being investigated. Blades for the Sandia 5-m turbine were ordered extruded in the NACA (.85) 515 section with a 15.24 cm chord. This camber would cause the camber line to coincide with the trajectory of a point at the perpendicular intersection of a radial line from the axis of rotation to the equatorial blade element at its 50% chord location. Two sets of two blades each were bent to the straight line - circular arc - straight line troposkein approximation planform, one set with the camber concave outward from the axis of rotation and one concave inward. The first set was to investigate the first postulate stated while the second would address the second. Both blade sets were run, but it was found that the performance differences (from the nominal NACA 0015 geometry) measured fell within the measurement uncertainties of the 5-m data gathering system. In order to amplify these differences to discernable magnitudes, a second pair of blade sets were ordered extruded in the NACA (2.34)515 section. (Although the first blades were ordered with a 0.85% camber, they were actually extruded to a 1.17% value. The 2.34% camber of the second blade sets was chosen because it is double that of the first.)

Blade Offset and Preset Pitch

Mounting blades of symmetrical cross-section with some preset pitch or incidence angle (β) can also potentially take advantage of the upwind-downwind and advancing-retreating flowfield differences. Computer simulations[3,4] indicate that β's of only a few degrees ($< \pm 5°$) lead to large changes (up to 25% or so) in peak efficiency and peak output power. Varying the chordwise location where the position vector from the axis of rotation perpendicularly intersects the blade element can also utilize the flowfield differences. The mechanism here is to allow blade element normal forces to contribute (positively and negatively) to the turbine turning torque. Current design practice does not significantly include these contributions as the chordwise mounting point is very near the blade element center of pressure.

A parametric experimental series is currently being run on the Sandia 5-m turbine which combines both of these effects. It is implemented by mounting the blade ends on rack-like devices which allow the radius vector from the tower centerline to normally intersect the blade chord at chordwise locations of between 180% chord behind and 77% chord ahead of the blade leading edge in roughly 13% chord increments. This range corresponds to blade β's at the equatorial plane of -7° to +3° (see Fig. 1). Some preliminary results are given in Figs. 2 and 3. It can be seen that these offsets have a large effect on both peak power and peak efficiency.

A second series of preset pitch experiments is also planned. This series involves pitching only the circular arc portion of the turbine blade. Single hinge points located at the 30% chord location at the extremeties of the curved portion will be oriented such that rotation of the curved portion about an axis parallel to the tower centerline is possible.

Blade Blowing

As mentioned previously, maximum rotor power is governed by maximum lift coefficient, $C_{\ell max}$, and the drag associated with operation at that condition. This may be governed actively as well as by the passive means described earlier. One scheme for active governing of maximum power is suggested by the fact that the hollow extruded aluminum blades when rotating act as centrifugal pumps. An experiment waiting to be run on the Sandia 5-m VAWT involves the use of blades into each of which have been drilled over 1000 circular holes of 0.13 cm diameter set 0.32 cm on center. These holes are placed on both sides of each blade at the 40% chord point and symmetrically distributed about the equatorial plane. By valving the ends of the blades, air volume flow through the holes may be controlled. At the maximum rotor power output operating condition, simple momentum and pumping power considerations indicate an 18% reduction in rotor power. Additionally assuming that 60% of each blade's lift is spoiled by this blowing suggests that the rotor will need to be externally powered in order to maintain rotational speed. Actual power loss will probably fall some place between these two extremes.

Blade Sections Designed Specifically for VAWT Application

Typical airfoil sections designed for aviation purposes exhibit low drag over a limited angle of attack range, high maximum lift coefficients, and gentle stall characteristics. This set of conditions is far from ideal when considering VAWT applications. Recently, attempts have been made to design an airfoil section which will exhibit low drag over a wider angle of attack range, a lower $C_{\ell max}$, and more abrupt stall than those sections currently available. Such profiles, when used as VAWT blade elements, will lower cut-in windspeed, raise peak efficiency, and lower maximum rotor power. Drag polars for an 18% thick laminar flow section intended to be used as a VAWT blade element is shown in Fig. 4. For comparison's sake, similar polars for the NACA 0015 airfoil is given in Fig. 5. Both sets were generated using the Eppler section characteristic synthesizer.[5] It is felt that typical VAWT flowfield turbulence levels are generally low enough that maintenance of laminar flow may be reasonably expected. It is currently intended to extrude a 15% thick profile having characteristics similar to the ones shown in Fig. 4 for testing on the Sandia 5-m turbine some time later in this year.

SUMMARY

A number of VAWT experiments, planned and ongoing, have been described which are intended to increase understanding of VAWT aerodynamics for the purposes of reducing VAWT cost of energy and increasing system reliability. Along with the analytical tools currently in use and under development, these experiments will hopefully provide the basis for the next generation of more cost-effective and reliable vertical axis wind turbines.

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NOMENCLATURE

A_s	Turbine swept area
C	Blade Chord
C_ℓ	Blade airfoil section lift coefficient = $\ell/(1/2)\rho_\infty V_\infty^2 c$
C_d	Blade airfoil section drag coefficient = $d/(1/2)\rho_\infty V_\infty^2 c$
C_p	Power coefficient, $Q\omega/(1/2)\rho_\infty V_\infty^3 A_s$
d	Blade airfoil section aerodynamic drag
K_p	Power coefficient, $Q\omega/(1/2)\rho_\infty A_s(R\omega)^3 = C_p/X^3$
L	Blade length
ℓ	Blade airfoil section aerodynamic lift
Q	Turbine torque
R	Turbine maximum radius
Re	Chord Reynolds number, $\rho_\infty R\omega c/\mu_\infty$
V_∞	Freestream velocity
X	Turbine tipspeed ratio, $R\omega/V_\infty$
α	Blade section angle of attack
μ_∞	Freestream viscosity
ρ_∞	Freestream density

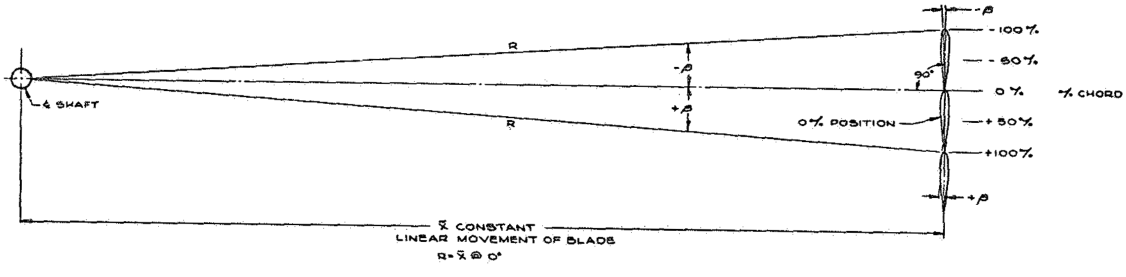

FIGURE 1. Definition of Blade Preset Pitch and Offset

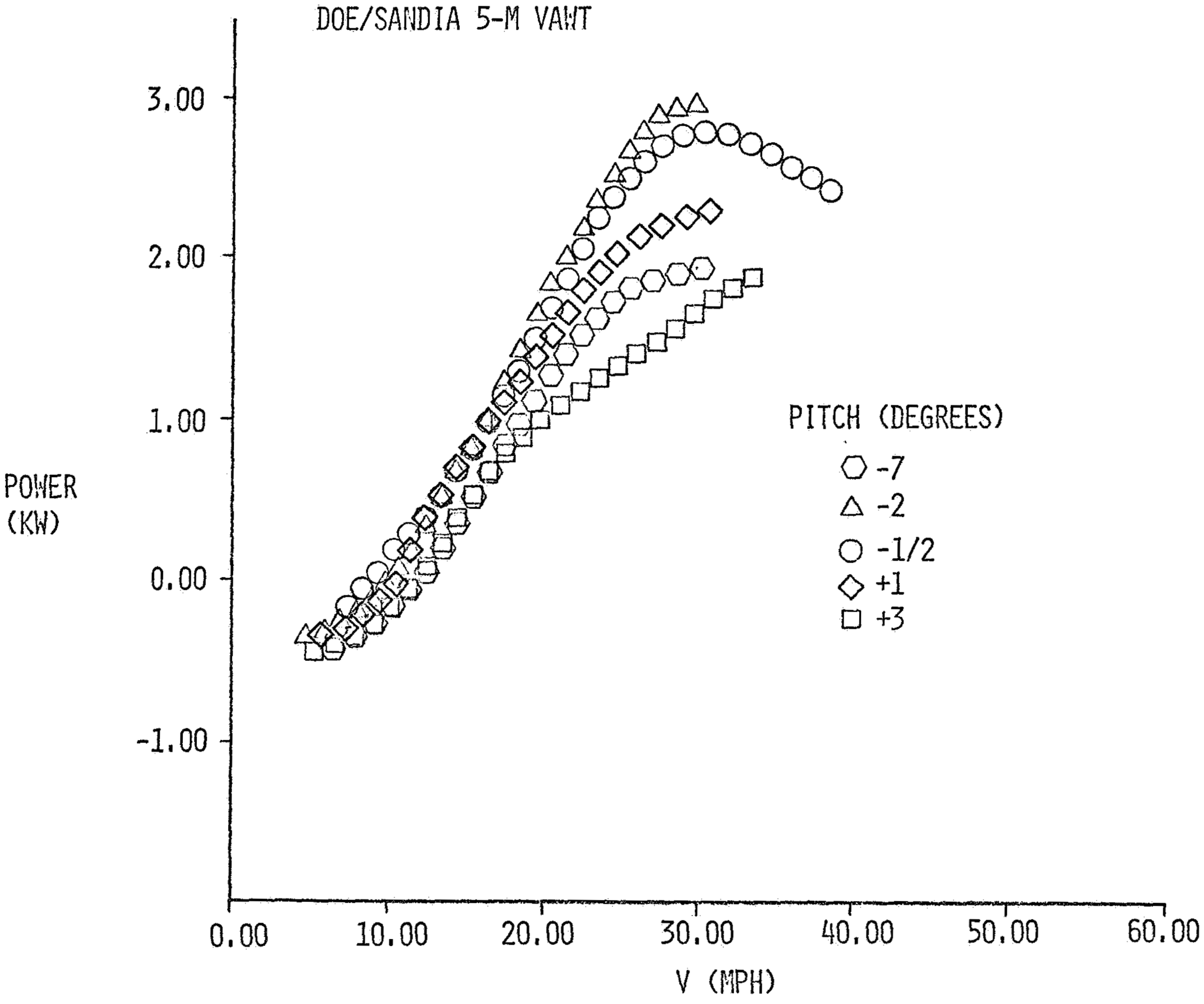

FIGURE 2. Preset Pitch/Blade Offset Rotor Power vs Windspeed, Sandia 5-m VAWT

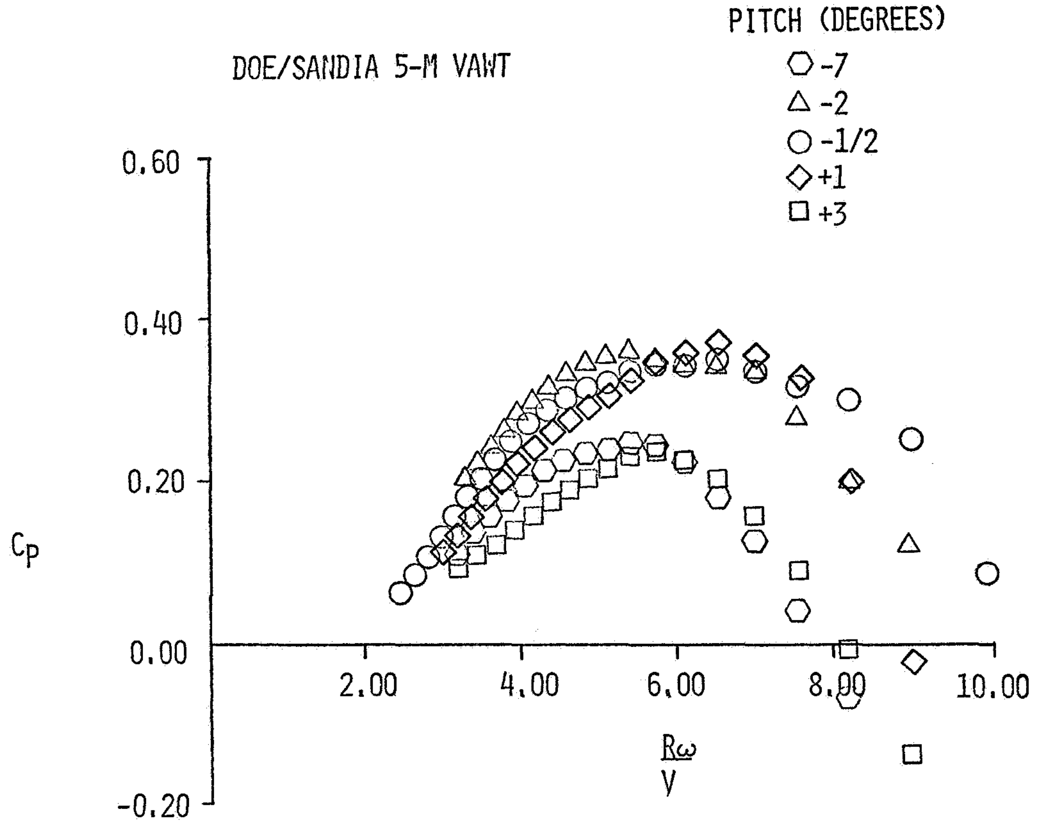

FIGURE 3. Preset Pitch/Blade Offset Power Coefficient vs Tipspeed Ratio, Sandia 5-m VAWT

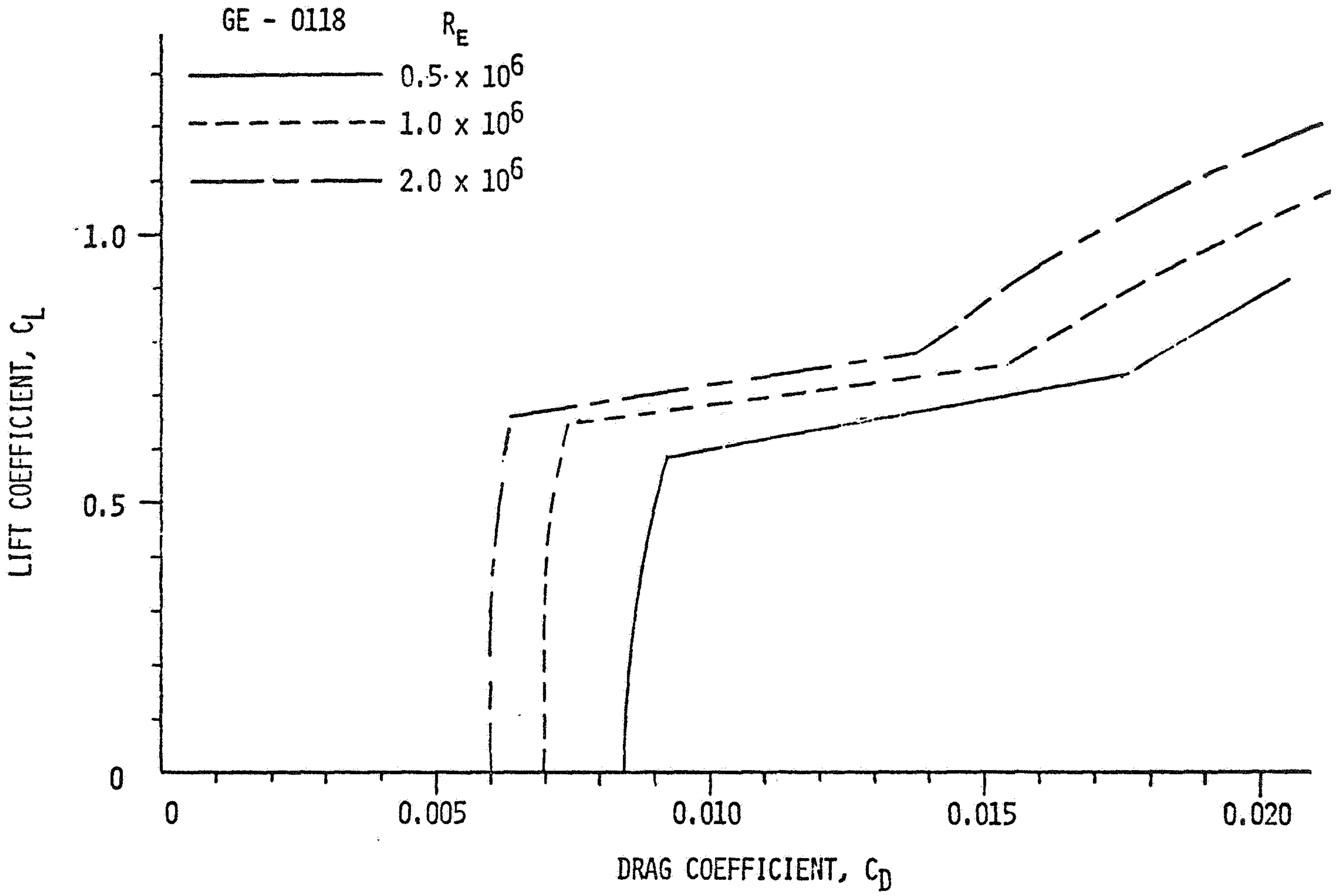

FIGURE 4. Predicted Drag Polars for 18% Thick Candidate VAWT Blade Element Section

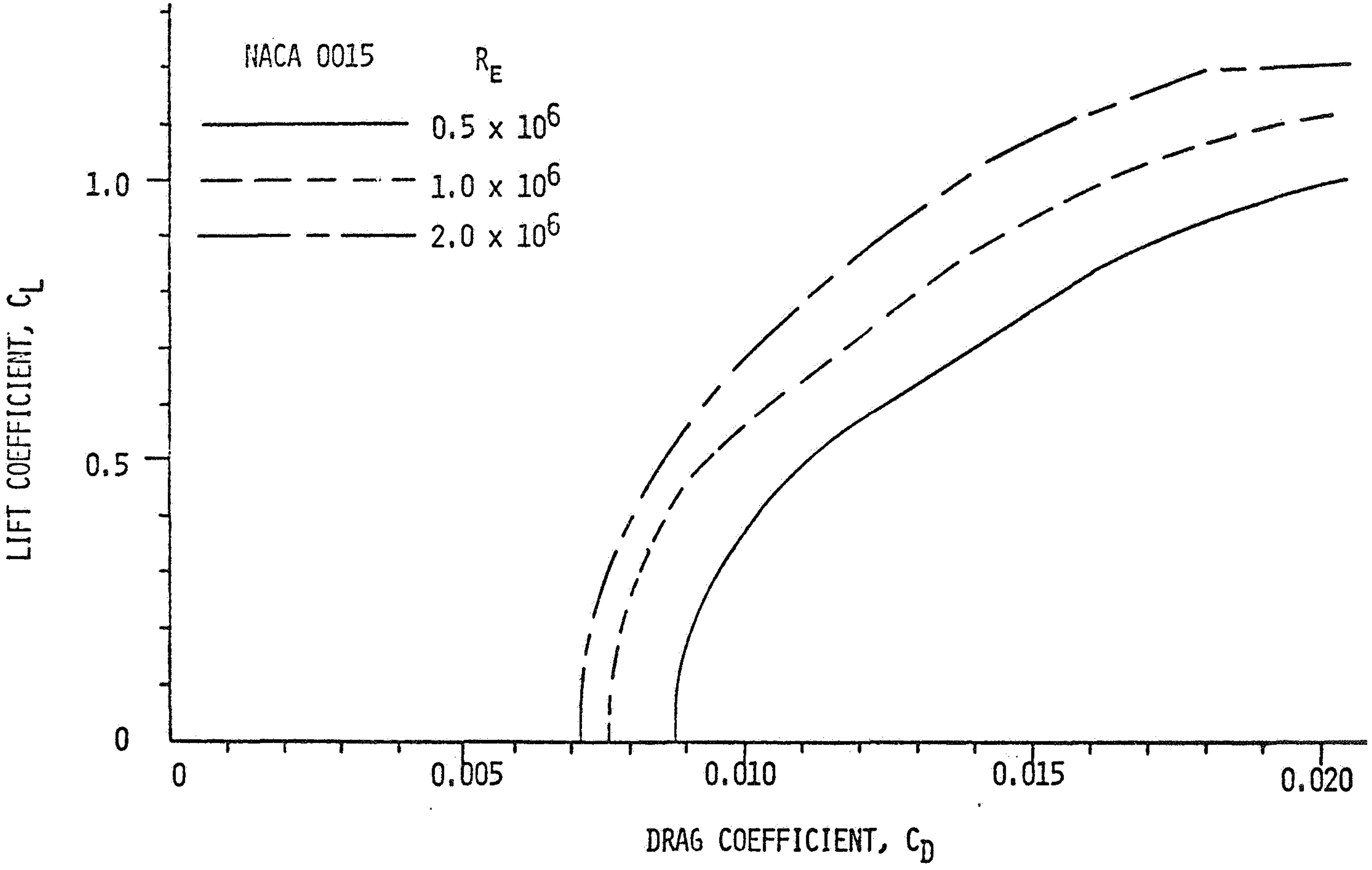

FIGURE 5. Predicted Drag Polars for NACA 0015 Airfoil Section

QUESTIONS AND ANSWERS

P.C. Klimas

From: J.A.C. Kentfield

Q: Have Sandia Labs. considered mounting a floating (i.e., trailing out in the wind) airfoil around the circular tube tower? This should reduce the tower wake on the downstream blade.

A: *This concept has been discussed at Sandia.*

From: N.H. Hubbard

Q: Will your blade pressure measurements include high frequency pressure fluctuations on the blade surface?

A: *I don't recall the frequency response specifications of the Entron, Inc., EPF 200-10 semiconductor transducers, but they are sensitive enough to see any fluctuations currently considered important. Each pressure will be sampled over a 20 millisecond interval.*

From: Anonymous

Q: At the beginning of your talk, you said you wanted to <u>decrease</u> C_{L_M} to move C_p curve to the right. Why?

A: *Decreasing* $C_{L_{Max}}$ *would* <u>*lower*</u> *the* C_p *curve by reducing output power. Since wind speeds corresponding to this point occur only for a low percentage of the time which the wind blows, cost reductions through lowering drive train requirements are proportionately greater than losses in annual energy, thus reducing cost of energy for the system. A second COE reduction comes through lowering drive train losses, these being proportional to rated power.*

From: J. Glasgow

Q:
1) How will you make Transient Pressure Measurements?
2) Comment in more detail what you expect to get from accelerometers with respect to dynamic stall.
3) Comment on wind speed measurements for Aero Performance Study = i.e. Distance Averaging Time, etc.

A:
1) *Transient pressure measurements will be made with semiconductor type transducers which will be sampled for 20 millisecond time intervals.*
2) *Hopefully the accelerometer measurements will help in interpreting the pressure measurements.*
3) *The wind speed measurements will be made by a directional cup anemometer located 7m above the turbine rotating tower. Using the well documented site wind shear profile the measured speed may be used to determine the ambient speed at any desired height.*

From: Bill Wentz

Q: 29 transducers--how many chordwise points will you obtain? How many spanwise?

A: *The 29 transducers are all at one spanwise location. There are 14 on both the upper and lower surfaces and one at the leading edge.*

From: G.P. Tennyson

Q: Should you not also consider airfoil cambering as it relates to power optimization (or some such) in addition to symmetrical-about-the-arc-of-rotation cambered airfoils?

A: *Yes, this is currently being investigated.*

From: Art Smith

Q: Does increasing pitch narrow down the streamtube thereby increasing power available by increasing the velocity at the blade?

A: *Increasing pitch would narrow down the streamtube at some locations but increase it at others.*