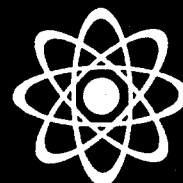
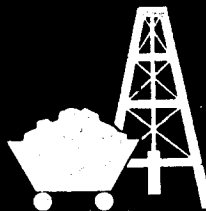
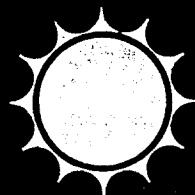


# The Vertical-Axis Wind Turbine "How It Works"

B. F. Blackwell



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THE VERTICAL-AXIS WIND TURBINE  
"HOW IT WORKS"

B. F. Blackwell  
Aerodynamics Projects Department 5620  
Sandia Laboratories  
Albuquerque, New Mexico 87115

ABSTRACT

A qualitative description of how a vertical-axis wind turbine works is presented, and some of the advantages over a conventional propeller-type wind turbine are discussed.



## THE VERTICAL-AXIS WIND TURBINE "HOW IT WORKS"

In 1925, G. J. M. Darrieus, Paris, France, proposed for United States patent a new type of windmill designed for the generation of power. The patent, issued in 1931 as Number 1,835,018, was for a "turbine having its rotating shaft transverse to the flow of the current." A similar wind turbine was independently developed by the National Aeronautical Establishment of the National Research Council of Canada in the early 1970's.

Figure 1 shows a photograph of a small-scale model vertical-axis wind turbine. Each blade is a symmetric airfoil in cross section and is curved in the shape that a perfectly flexible cable of uniform density and cross section would assume if spun about a vertical axis. This blade shape has been designated troposkien (from the Greek: τροπος, turning; and σχοινιον, rope). If the blades are preformed in the troposkien shape, rotation will not cause the blades to bend and thus the stresses will be pure tension.

The vertical-axis wind turbine offers several advantages over the conventional propeller-type wind turbine:

1. Ability to accept wind from any direction.
2. The generator can be placed at ground level, without costly bevel gearing, and will thereby allow simpler tower construction and less maintenance.
3. Lower fabrication costs because of simple tower construction and reduced blade fabrication costs.

The operational principle of the vertical-axis wind turbine is analogous to the aerodynamics of a wing (airfoil). When a fluid flows over an airfoil, forces are exerted on the airfoil. These forces are generally divided into lift and drag components; the drag force is parallel to the wind, while the lift force is perpendicular to the drag force. The angle between the chord line and the wind direction is called the angle of attack. For a symmetric airfoil, as shown in Figure 2, the chord line corresponds to the centerline of the airfoil cross section. The general characteristic of most airfoils is that the ratio of lift-to-drag (L/D) increases with increasing angle of attack up to the point where the flow separates from the airfoil. This separation is generally referred to as stall. Once the angle of attack is sufficiently large to cause stall, the lift-to-drag ratio decreases with increasing angle of attack. For optimum aerodynamic performance, the stalled condition should be avoided.

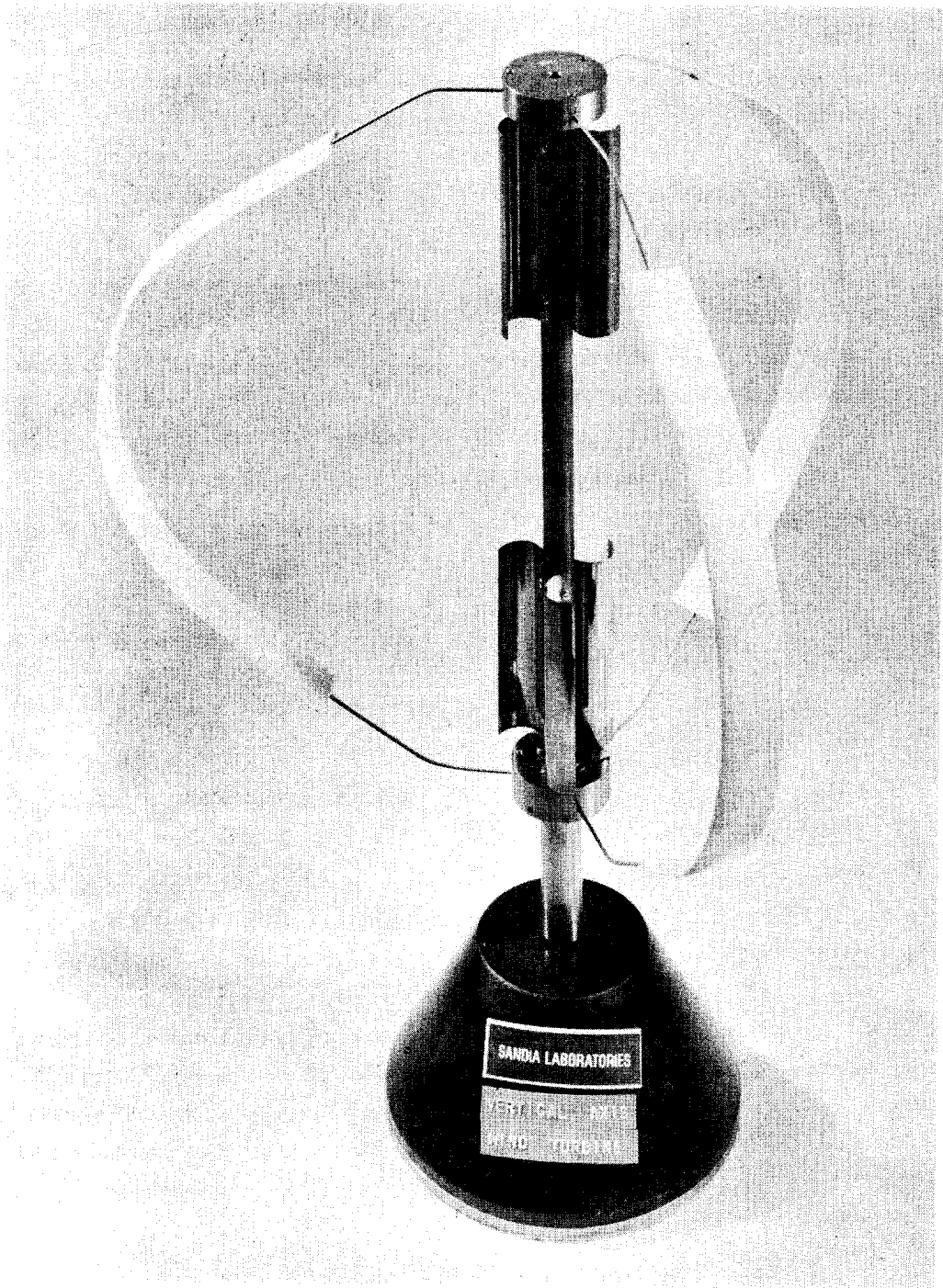


Figure 1. Vertical Axis Wind Turbine

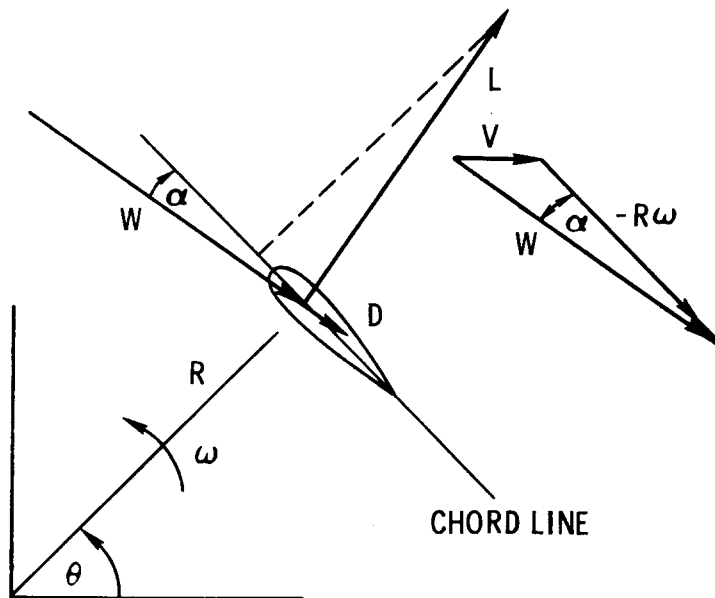


Figure 2. Aerodynamic Forces Acting on a Rotating Airfoil

Because the vertical-axis wind turbine has rotating airfoils, it presents a slightly different condition. First, the wind felt on a rotating airfoil is not simply the absolute wind speed. Instead, the velocity of the wind relative to the blade is the absolute wind velocity,  $V$ , minus the absolute blade velocity,  $R\omega$ . This vector velocity difference is shown in Figure 2. For a rotating airfoil, the angle of attack is the angle between the relative wind speed,  $W$ , and the chord line. As illustrated in Figure 2, the angle of attack,  $\alpha$ , depends on the wind speed,  $V$ , the rotational speed,  $R\omega$ , and the blade position angle,  $\theta$ . In the figure,  $V$  and  $R\omega$  are drawn so that  $R\omega/V$  corresponds to an angle of attack of approximately 12 degrees at the blade position indicated. For a given blade position, the angle of attack decreases with increasing relative rotational speed ( $R\omega/V$ ). Therefore, for a sufficiently high relative rotational speed ( $R\omega/V$ ), the airfoil is never stalled during a revolution. However, at a low relative rotational speed ( $R\omega/V$ ), the airfoil will be stalled over an appreciable portion of a revolution. In that the blade stalls at low relative rotational speeds, the aerodynamic performance will be very poor for small  $R\omega/V$ .

The forces that cause rotation are determined by projecting the lift force,  $L$ , and the drag force,  $D$ , onto the direction of the chord line of the airfoil. The chordwise component of the lift force (Figure 2) tends to cause rotation in a counterclockwise sense, while the chordwise component of the drag force opposes this motion. As long as the chordwise lift force is greater than the chordwise drag force, the driving torque will always be positive.

As stated above, the aerodynamic performance is poor at low relative rotational speeds because of airfoil stall. The performance is also poor at high relative rotational speeds but for an entirely different reason. As  $R\omega/V$  increases, the angle of attack,  $\alpha$ , decreases. Consequently,

the chordwise component of lift decreases with decreasing  $\alpha$  (see Figure 2). Also, the lift-to-drag ratio goes to zero as the angle of attack goes to zero. From the above discussion, a composite picture of the aerodynamic performance can be envisioned: poor performance occurs at both low and high relative rotational speeds; best performance occurs at intermediate values of  $R\omega/V$  because the angle of attack is sufficiently large for high values of  $L/D$  but not large enough to cause stall. Figure 3 illustrates this anticipated behavior. The efficiency of the vertical-axis wind turbine is comparable to that of a conventional horizontal-axis wind turbine, i. e. , about 40 percent of the available stream energy can be extracted.

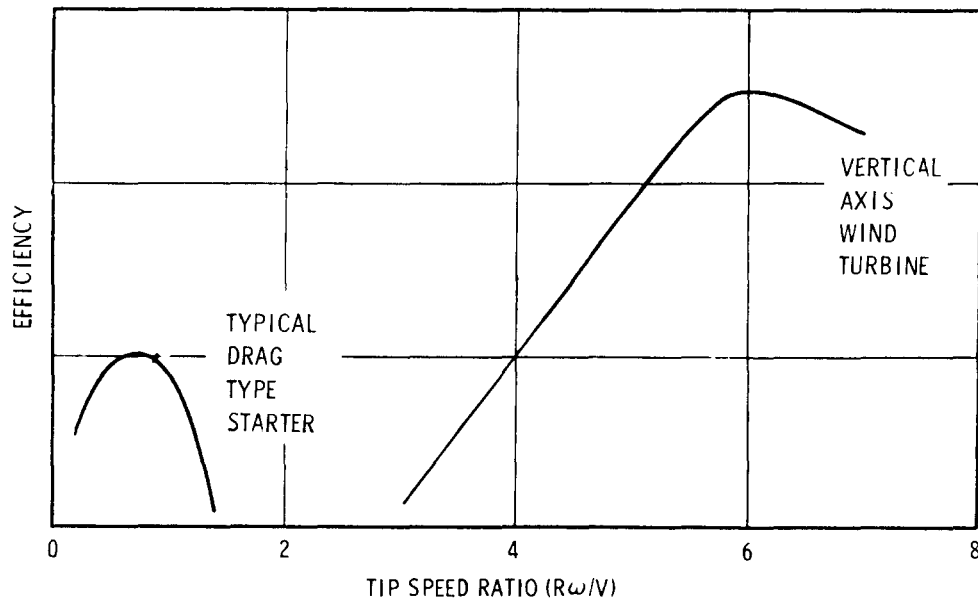


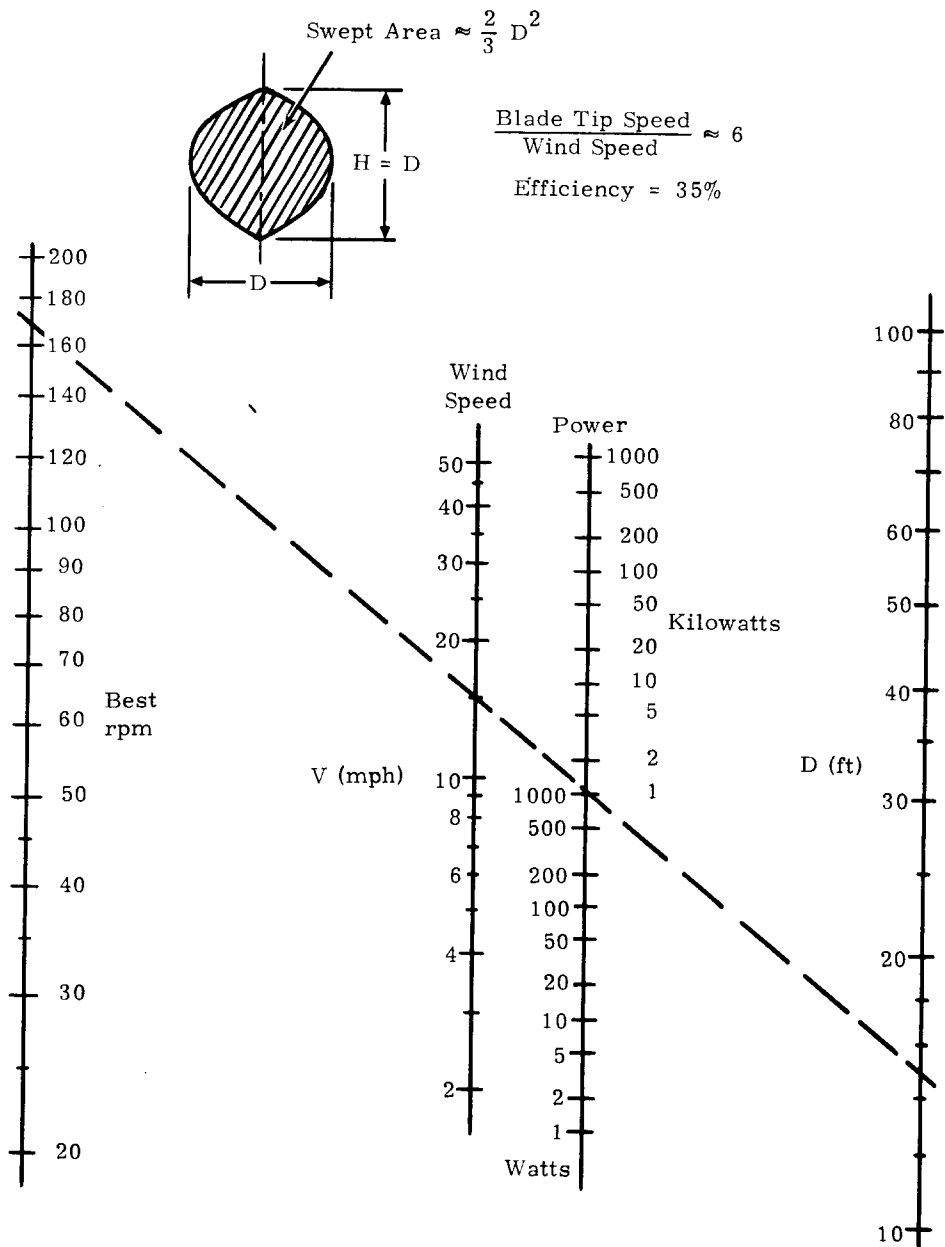
Figure 3. Performance Curves

Because the blades stall at low relative rotational speeds, some type of auxiliary device must be used to start the system. The drag buckets attached to the central shaft (Figure 1) have been used as a starter. They have good torque characteristics at low relative rotational speeds. Once the starter has driven the system to a relative rotational speed of  $R\omega/V \approx 3$ , the blades begin to drive. The starter is sized so that, when the blades are operating at the most efficient condition, the starter is also operating at the most efficient condition. The efficiency of the starter is shown in Figure 3 together with the efficiency of the blades.

In order to determine the size of a vertical-axis wind turbine necessary to produce a given power output for some wind speed, a performance nomogram, reproduced from Reference 4, is shown in Figure 4. In this nomogram, the load on the wind turbine is assumed to be varied so that it always operates at the most efficient tip-speed ratio ( $R\omega/V \approx 6$ ).



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Example (broken line): Given wind speed = 15 mph,  
diameter D = 15 feet, find output shaft power and  
operating shaft speed for maximum power.  
Shaft speed = 168 rpm; shaft power = 1080 watts.

Figure 4. Vertical-Axis Wind Turbine Performance Nomogram

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Dr. Alfred J. Eggers, Jr.  
Assistant Director for Research  
Applications

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Dr. Ralph Muraca  
Mail Stop 317  
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Dr. Michael Wahlig  
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Energy and Environment Division  
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Berkeley, California 94720

Mr. Billy Hudson  
University of California  
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Argonne, Illinois 60439

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