AMERICAN NATIONAL STANDARD

ASME/ANSI PTC 42-1988

Wind Turbines

PERFORMANCE TEST CODES

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THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center
345 East 47th Street New York, N.Y. 10017

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FOREWORD

(This Foreword is not part of ASME/ANSI PTC 42-1988.)

The Performance Test Codes Committee, at its March 1979 Administrative meeting, authorized the formation of a Code Technical Committee to explore the possibility of writing a test code on wind turbines. This Committee was organized on January 30, 1981. At its organizational meeting, the Committee proposed the writing of PTC 42 on Wind Turbine Generators.

This proposal was approved by the Performance Test Codes Supervisory Committee. This Code was approved by the Board on Performance Test Codes on March 3, 1988. It was further approved as an American National Standard by the ANSI Board of Standards Review on November 17, 1988.

PERSONNEL OF PERFORMANCE TEST CODES COMMITTEE NO. 42 ON WIND TURBINES

(The following is the roster of the Committee at the time of approval of this Standard.)

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K. G. Grothues, Southern California Edison Co.
T. M. Hasbrouck, Hamilton Standard
T. Hillesland, Jr., Pacific Gas and Electric Co.
W. Lucas, General Electric Co.
C. D. Maytum, U. S. Bureau of Reclamation
W. W. Wiesner, Boeing Aerospace Co.
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SECTION 0 — INTRODUCTION

0.1 This Code provides standard instructions for conducting performance tests of wind turbines. It is based on the use of accurate instrumentation and the best analytical and measurement methods and procedures available, and is intended to produce results of the highest accuracy consistent with good engineering practice. For the purpose of this Code, the term "wind turbine" (WT) is applicable to a machine that converts kinetic wind energy into electrical energy. This Code was specifically compiled for WT systems of 100 kW or more, but is applicable to all sizes. WT performance is measured by the amount of electrical energy derived from the wind under known conditions. The testing procedures may be simple or complex depending on the size and complexity of the WT and the site wind conditions. Only the relevant portions of the Code need to be applied to any given test.

0.2 This Code is recommended for use in conducting the performance portion of WT acceptance tests. If so used, any deviations from the procedures in this Code must be agreed upon in writing by the parties to the test. In the absence of a written agreement regarding deviations, Code requirements will be mandatory.

0.3 For purposes other than acceptance testing, the party or parties to the test may use this Code as a guide in developing tests suitable for the intended purpose.

0.4 This Code complies with the provisions of the ASME Code on General Instructions (PTC 1), and the ASME Code on Definitions and Values (PTC 2). In addition, unless otherwise specified in this Code, all instrumentation shall comply with applicable provisions of the Supplements on Instruments and Apparatus (PTC 19 Series).

SECTION 1 — OBJECT AND SCOPE

1.1 PRIMARY OBJECTIVE

The primary objective of this Code is to compare the net amount of electrical energy produced by the WT during a given period of time to the predicted test energy for the same period and the same wind speed histogram.

1.2 SECONDARY OBJECTIVES

This Code may be used for the following purposes:

(*a*) to compare the test power-versus-wind-speed curve to the reference power-versus-wind-speed curve;

(*b*) to compare the annual energy output calculated using the test power-versus-wind-speed curve with that calculated using the reference power-versus-wind-speed curve, for the same annual wind speed histogram;

(*c*) to determine the effects on WT performance of changes to subsystems and components of the WT or changes in the methods of operation for specified conditions at a given site;

(*d*) to compare the performance of the WT with the established performance of other WTs at the same or different sites.

1.3 SCOPE

This Code specifies the methods, procedures, and instrumentation for the field testing and reporting of WT performance. These procedures and practices were specifically compiled for WTs of 100 kW or more, but are applicable to all sizes.

1.4 APPLICABILITY

This Code is not intended to govern the conduct of general or specialized research, or for the development of subsystems and components. Nevertheless, when such testing is performed and results are intended for publication, it is recommended that testing and reporting proceed as nearly as is practical in harmony with this Code.

SECTION 2 — DEFINITIONS OF TERMS

2.1 GENERAL DEFINITIONS

annual energy, reference — energy output based on the reference power curve, the reference air density, and the reference annual wind speed histogram

annual energy, test — energy output calculated using the test power curve and the reference annual wind speed histogram

annual energy ratio — ratio of test annual energy output to the reference annual energy output

letter symbols — (Letter symbols used in this Code are listed in Table 2.1 and are defined in the paragraph in which they first appear.)

measured test energy — quantity determined directly from instrument readings without adjustment except for calibration

predicted test energy — calculated quantity determined from the reference power curve, adjusted for test air density, and the test wind speed histogram

reference power curve or reference power-vs-wind-speed curve — curve, series of curves, or tabulation of the power output predicted for a specific WT as a function of wind speed and air density

reference power-vs-wind-speed curve or reference power curve — curve, series of curves, or tabulation of the power output predicted for a specific WT as a function of wind speed and air density

rotor — aerodynamic assembly of blades, hub attachments, and shaft which converts kinetic wind energy to mechanical rotational energy

test energy ratio — ratio of measured test energy to predicted test energy. Test energy ratio is the primary measurement of wind turbine performance.

test power-vs-wind-speed curve or test power curve — curve, series of curves, or tabulation of the measured WT power output as a function of wind speed at the reference air density

test run — group of consecutive test segments. Each test run provides a period of operation of the WT in its energy conversion mode, uninterrupted by transients such as starting and stopping. A series of test runs comprises the performance test.

test segment — time period for which increments of measured test energy and predicted test energy are determined. Typical segment durations are 5 to 10 min.

units — meters (m), kilograms (kg), hours (h), seconds (s), millibars (mbar), degrees Celsius (°C), and kilowatts (kW) are the primary units of this Code. For convenience, other customary units may also be included (Note: 1 mbar = 100 Pa).

wind turbine (WT) — rotary machine which converts kinetic wind energy into electrical energy

2.2 METEOROLOGY DEFINITIONS

air density, mean test — average test air density for all test segments

air density, reference — air density to which measured test energy is adjusted for purposes of obtaining a test power curve and an annual energy ratio. Mean test air density is a recommended reference in order to minimize adjustments to the measured data.

air density, test — density of air at the test site and at the test altitude during a test period. This is a calculated quantity depending upon the measured air temperature and barometric pressure and the altitude of the measuring instruments. Test altitude, rather than sea level, is used in order to minimize adjustments for air density differences.

distance constant — a measure of anemometer response rate, equivalent to the run of wind necessary for the anemometer output to indicate 63% of the final value for a step function change in wind speed

reference elevation — vertical distance of the geometric center of the swept area of the rotor above the ground

test altitude — altitude (above mean sea level) of the geometric center of the swept area of the WT rotor

wind azimuth — wind direction measured as an angle clockwise from true north

wind shear — vertical gradient of the horizontal wind speed

TABLE 2.1
LETTER SYMBOLS

Symbol	Definition	Paragraph
AC	Alternating current	2.3
AER	Annual Energy Ratio, E_{ta}/E_{ra}	5.8
a_1, a_2	Angles which define the range of wind directions for which test data are invalid (Fig. 4.2)	4.3.2
B	Barometric pressure (Fig. 4.1)	4.9.1
°C	Degrees Celsius	2.1
C	Weibull scale constant	5.3.2
D	Rotor diameter (Fig. 4.2)	4.2.3
D_t	Duration of test	5.6
dE_m	Measured net test energy output during segment	5.4.2
dE_p	Predicted net test energy output calculated for segment	5.5
dE_t	Adjusted net test energy output during segment	5.7.1
dt	Duration of test segment	5.5
$E1$	System energy output (Fig. 4.1)	4.9.1
$E2$	Auxiliary energy	4.9.1
E_m	Total measured test energy	5.6
E_p	Test predicted test energy	5.6
E_{ra}	Reference annual energy output	5.3.3
E_{ta}	Total annual test energy output	5.8
H	Rotor height (Fig. 4.2)	4.2.4
h	Hours	2.1
h_o	Reference elevation of the rotor (Fig. 4.2)	4.2.3
h_1	Distance between levels A and B (Fig. 4.2)	4.2.4
i	Identifying index of a run (consecutive from 1 to I)	5.4.1
j	Identifying index of a segment (consecutive from 1 to J)	5.4.1
k	Weibull shape constant	5.3.2
k	Identifying index of bin (consecutive from 1 to K)	5.7.1
kg	Kilograms	2.1
kVA	Kilovolt-amperes	4.6.4
kW	Kilowatts	2.1

TABLE 2.1 LETTER SYMBOLS (CONT'D.)

Symbol	Definition	Paragraph
L	Distance from the WT to the meteorological tower	4.2.3
MW	Megawatts	5.3.3
m	Meters	2.1
mbar	Millibars	2.1
P_g	Real generator power (Figs. 2.1 and 4.1)	4.9.1
P_r	Reference power output	5.3.1
$P_r\ (V_t, \varrho_t)$	Reference power at the test wind speed and the reference air density	5.7.1
$P_r\ (V_t, \varrho_r)$	Reference power at the test speed and the test air density	5.7.1
P_t	Test power output	5.8
P_{tb}	Test power output for each wind speed bin, at bin's mean wind speed and reference air density	5.7.2
Q_g	Reactive generator power (Figs. 2.1 and 4.1)	4.9.1
S_g	Apparent generator power (Fig. 2.1)	2.3
T	Air temperature (Fig. 4.1)	4.9.1
t	Date and time-of-day (Fig. 4.1)	4.9.1
TER	Test Energy Ratio, E_m/E_p	5.6
$\overline{V}$	Annual average wind speed	5.3.2
V_a	Wind speed adjustment, a function of measured wind speed and azimuth	5.2
V_b	Bin mean wind speed	5.7.1
V_m	Measured wind speed (Fig. 4.1)	4.9.1
V_t	Test wind speed	5.2
WT	Wind turbine	2.1
Γ	Gamma function	5.3.2
ΔE_m	Measured net test energy output during run	5.4.2
ΔE_p	Predicted net test energy output for a run	5.5
ΔE_{mb}	Bin cumulative measured energy output (at test air densities)	5.7.1
ΔE_{ra}	Reference annual energy output in a wind speed range	5.3.3
ΔE_{ta}	Test annual energy output in a wind speed range	5.8
ΔE_{tb}	Bin cumulative adjusted test energy output (at reference air density)	5.7.1

TABLE 2.1 LETTER SYMBOLS (CONT'D.)

Symbol	Definition	Paragraph
$\Delta E1$	System energy output measured during run	5.4.2
$\Delta E2$	Auxiliary energy used during run	5.4.2
Δt	Duration of run	5.4.2
Δt_a	Annual duration of V_t in a wind speed range	5.3.3
Δt_b	Bin cumulative test time	5.7.1
θ	Phase angle between the P and S vectors in an electric power vector diagram (Fig. 2.1)	2.3
ϱ	Test air density	5.3.1
ψ	Measured wind azimuth (Fig. 4.1)	4.9.1

wind speed, measured — magnitude of the average horizontal wind velocity measured during a test segment

wind speed, test — measured wind speed adjusted, if required, to represent the site free-stream wind speed at the center of the swept area of the rotor

wind speed bin — narrow wind speed range for sorting test data

wind speed histogram, reference annual — frequency distribution of wind speeds expressed in terms of hours per year for a stated speed range and totaling 8760 h. May be hypothetical (such as the Rayleigh or Weibull distribution) or based on site test data.

wind speed histogram, test — frequency distribution of wind speeds during the performance test expressed in terms of hours for a stated speed range and totaling to the test duration

2.3 ELECTRICAL DEFINITIONS

burden — electrical load imposed on current and potential transformers by watt and var transducers and other instrumentation

electrical energy, auxiliary — electrical energy required for conducting the performance test but not required for necessary WT operations such as control power, lighting, heating, cooling, or power conditioning

electrical energy, net — sum of system electrical energy and auxiliary electrical energy

electrical energy, system — electrical energy output of the WT to the electrical distribution system (or load)

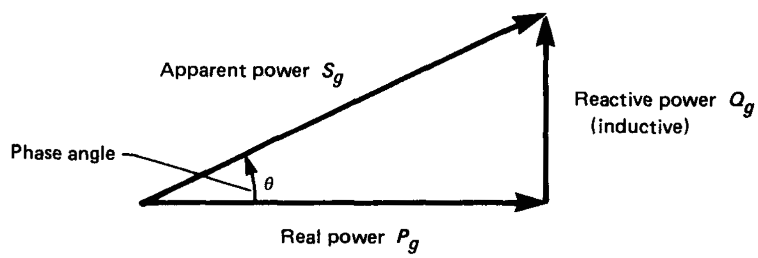
power, apparent — product of voltage and current

power, reactive — average rate of energy borrowed and returned once each cycle in an AC electric system. The magnetization of iron-core (inductive) devices such as transformers and induction machinery causes the current waveform to lag behind the voltage waveform. Capacitive devices cause the current waveform to lead the voltage waveform. Although the average energy transferred by purely inductive or capacitive currents is zero, a source for these currents must still be available.

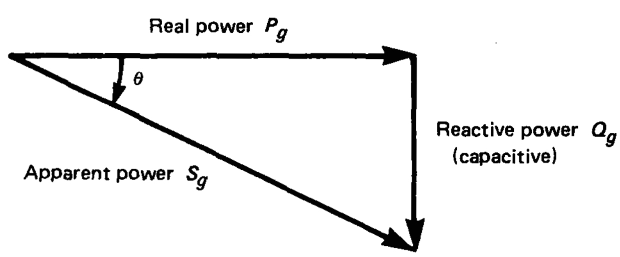
power, real — average rate of transfer of electrical energy

power factor — the ratio of real power to apparent power, which is also equal to the cosine of the phase angle θ between the sinusoidal voltage and current waveforms. The phase angle θ is also the angle between the real and apparent power vectors in the vector diagram (Fig. 2.1).

power vector diagram — geometric illustration of functional relationship between apparent, real, and reactive electrical powers, as shown in Fig. 2.1. Because no average energy is transferred by reactive power, the capacitive and inductive "powers" are shown as vectors at right angles to the real power vector. The usual sign convention for reactive power is positive for lagging (inductive) currents, as shown in Fig. 2.1, sketch (a). Reactive power is negative for leading (capacitive) currents, as shown in Fig. 2.1, sketch (b).



(a) When reactive power is dominated by magnetization requirements, it is supplied externally *by* the electrical distribution system and is positive in sign.



(b) When reactive power is dominated by capacitive devices, it is supplied *to* the electrical distribution system and is negative in sign.

FIG. 2.1 ELECTRIC POWER VECTOR DIAGRAM

SECTION 3 — GUIDING PRINCIPLES

3.1 INTRODUCTION

The methods to be followed in conducting a WT performance test are similar to those followed with more conventional prime movers, except that special provisions must be made due to the unsteady nature of the wind [1].

3.2 PRINCIPAL MEASURE OF WT PERFORMANCE

The principal measure of WT performance is net electrical energy output [2] rather than instantaneous power output. The objective of a performance test is to compare the actual WT energy output during a given period of time to the predicted test energy output based on wind speed and air density during that same period of time.

3.3 PRINCIPAL OBJECTIVE

The principal objective of a WT performance test is a comparison of measured and predicted energy outputs for the test period.

3.4 SECONDARY OBJECTIVES

Secondary objectives are a test power-vs-wind-speed curve and a comparison of annual energy output calculated from test data with a reference annual energy output.

3.5 ENERGY MEASUREMENTS

Direct measurements of net electrical energy output will be made for comparison with output calculations made according to a reference energy calculation model agreed upon by the parties to the test.

3.6 METEOROLOGICAL MEASUREMENTS

While the WT is operating, wind speed, wind azimuth, ambient air temperature, and barometric pressure are measured near the WT and recorded. The frequency of these meteorological measurements shall be sufficient to achieve the required accuracy in predicting the energy output for each test run. These measurements shall be taken so as not to be influenced by the presence or operation of the WT. Recording of humidity is not required, since it has a negligible (though calculable) effect on air density.

3.7 PERMITTED ENERGY ADJUSTMENTS

For the primary objective of comparing measured and predicted test energies, no adjustments shall be made to the measured test energy. Adjustments for differences in air density or for anemometer correlation (see para. 4.2.4) shall be made to the predicted test energy.

3.8 EFFECTS OF WT ORIENTATION

No adjustments shall be made to either measured or predicted test energies for differences between the orientation of the WT and the wind azimuth. Any effects of orientation differences shall be included in the reference power curve (para. 3.10.5). Calculation of these effects should be consistent with any limitations on wind shear and turbulence agreed upon prior to the test (para. 3.10.9).

3.9 REPRESENTATION

Each party to the test shall assign a person responsible for the determination of test completeness, with authority to accept or reject the results and conclusions of the test. Each party shall act to establish, along with the others, the agenda, conduct of the test, and criteria for acceptance or rejection of the test results. All parties shall have equal rights in determining the test.

3.10 ITEMS ON WHICH AGREEMENT SHALL BE REACHED

(a) Object of the test and test acceptance criteria.

(b) Plan of test, including schedule, recording of readings and observations, and calculation of test results.

(c) Test Manager responsible for conducting the test, assigning test personnel, and submitting the final test report to the parties.

(d) Definition of the load, including allowable voltage range and power factor.

(e) Reference energy calculation model, including reference power curve, range of air densities, and reference annual wind speed histogram. This model may have the form of a tabulation of net-electrical-power-vs-wind-speed, a tabulation of net-electrical-energy-vs-wind-speed for a specified time increment, a computer model, or other performance algorithm. The reference energy calculation model shall be documented and included in the final report.

(f) Duration of the test and the minimum duration of an individual test run. Typical test durations (the number of test segments multiplied by test segment duration) are 30 to 70 hrs, with individual test runs at least 1 hr long.

(g) Test Segment Duration. In the absence of specific expert analysis of site, WT, and anemometer characteristics, a range of 5 to 10 min is recommended. Factors which may influence the test segment duration are discussed in [3] and [4].

(h) Minimum size and energy content of wind speed bins.

(i) A set of test wind conditions which defines required ranges of wind speed and azimuth, the minimum duration of operation for speeds and azimuths within these ranges, and limitations (if any) on wind shear and turbulence. Continuous operation is not required for determining durations.

(j) Adjustments to measured wind speeds.

(k) Corrections for deviations of test conditions from those specified, other than those defined in this Code.

(l) Criteria for interrupting the test (icing, hurricanes, extreme temperatures, rain, turbulence, etc.).

3.11 CONDITION OF WT BEFORE AND AFTER TESTING

3.11.1 Before tests are begun, the manufacturer of the WT shall determine that the equipment and instrumentation are in suitable condition for the test to be carried out. The manufacturer may make any permanent adjustments required to place the unit in proper operating condition, provided these adjustments are made prior to the test and remain in effect throughout the test.

3.11.2 Preliminary runs shall be made for the purpose of determining whether the WT system is in a safe and suitable condition for the conduct of a performance test. Such runs may be made for checking of instrumentation, adjustment of the WT, and training of personnel. After preliminary runs have been made, these runs may, by agreement, be included in the performance test.

3.11.3 At the conclusion of testing, the WT shall be fully operational and in the same condition of adjustment as throughout the test.

3.12 DURATION OF TEST OBSERVATIONS

The duration of WT performance testing will be governed by the actual site wind conditions. The controlling factor is the time required to record data sufficient to verify the performance of the WT over the range of wind speeds of interest. This may require several test runs in order to obtain the required variation in wind speed. The test should be structured according to the following.

3.12.1 Test runs and the recording of test run data shall begin after the WT has come up to speed and has been connected to the load.

3.12.2 Performance data shall be taken continuously and consecutively during a test run.

3.12.3 Transient parameters may be measured separately if they are part of the performance test. These parameters may occur during startup, running, and shutdown.

3.12.4 Standby energy may be measured separately if this parameter is part of the performance test.

3.13 NORMAL MAINTENANCE

Normal maintenance procedures may be followed between test runs, including both scheduled and unscheduled maintenance.

3.14 INCONSISTENT MEASUREMENTS

Inconsistent measurements influencing the results of the test shall be resolved by locating and eliminating the cause of the inconsistency. If the inconsistent measurements were all made in accordance with Code procedures and if the inconsistency cannot be resolved, it shall be the duty of the Test Manager to reject the inconsistent measurements.

3.15 DATA REVIEW

Data review by the parties to the test shall be conducted immediately following the performance test. All test logs and records shall be critically examined to determine whether or not the specified operating conditions and requirements have been met. Adjustments of any kind, including rejection of data, shall be agreed upon by the parties and explained in the test report.

3.16 CALIBRATION OF INSTRUMENTS

Calibration of instruments shall be traceable to NBS standards, and records shall be available prior to the test. Recalibration at the conclusion of the test shall be made for instruments of primary importance which are liable to vary in their calibration as a result of use during the test or severe environmental exposure.

3.17 RECORD AND TEST REPORTS

Record and test reports are required for only such observations and measurements as apply and are necessary to attain the objective of the test. Test data shall be recorded as measured. Original data shall remain in the custody of the Test Manager. The original shall be reproduced to furnish copies to each of the parties to the test. Uncorrected values, method of correction, and corrected values shall be entered separately in the test record.

3.18 TOLERANCES

Tolerances are not considered in this Code. The test results shall be reported as computed from the test observations, only instrument calibrations having been applied. Certain of the measurements, however, may be subject to appreciable uncertainty. The expected limits are stated, where possible, in Section 4. Section 7 contains further discussion of the subject of measurement uncertainty.

SECTION 4 — MEASUREMENT PROCEDURES

4.1 INTRODUCTION

The Section contains detailed information on measurements required for conducting a WT performance test, including types and locations of instruments, calibration requirements, and recommended data recording methods. Supplementary information can be found in [5]. Figures 4.1 and 4.2 show schematically a typical arrangement of required equipment and the location of sensors for measuring the eight parameters which comprise the test data set. These parameters are described briefly in the following paragraphs.

4.1.1 Wind Speed. Wind speed is measured by duplicate anemometers located on a meteorological tower generally upwind of the WT and at the same elevation as the center of the area swept by the rotor. Measurements are averaged over a "test segment" time interval and this average wind speed is recorded.

4.1.2 Wind Azimuth. Wind azimuth, which is also averaged over the test segment time, is needed to determine (1) if the wind is in a valid or invalid sector (Fig. 4.2 and para. 4.3.2), and (2) the adjustment which correlates measured wind speed with the hypothetical free-stream wind speed at the center of the rotor area. The Code specifically prohibits adjusting predicted energy output to compensate for any error in the heading of the WT with respect to the wind azimuth.

4.1.3 Ambient Air Temperature and Barometric Pressure. Ambient air temperature and barometric pressure are used to calculate the air density during the test. The Code requires that temperature and pressure measurements be recorded at least every hour and permits interpolation to obtain air densities for each test segment.

4.1.4 System Energy. System energy output is metered at a location which is on the utility or user side of any electrical losses caused by equipment necessary for the operation of the WT. Watt-hour meters or other measuring devices of comparable accuracy are required for this critical measurement. System energy readings must be recorded at the beginning and end of each test run and at least hourly during the run.

4.1.5 Auxiliary Energy. Auxiliary energy supplied by the WT and consumed by equipment not necessary for the operation of the wind turbine may be either metered separately or calculated by an agreed-upon method. In either case, auxiliary energy is added to the system energy to obtain the net energy output of the wind turbine.

4.1.6 Generator Power. Generator power measurements are not required for determining the Test Energy Ratio, which is the primary measure of wind turbine performance. However, a secondary Code objective is to obtain a power curve. To do this, the energy output for each test segment must be known. In the event that energy measurements are not made for each segment, generator power measurements may be used for interpolation between energy readings. In addition, generator power measurements are strongly recommended for verifying WT operating parameters and the consistency of energy measurements.

4.1.7 Date and Time. Date and time-of-day measurements subdivide test runs into test segments and coordinate all the test measurements.

4.1.8 In the absence of special agreements to the contrary, this Section presents the mandatory requirements for the instruments, methods, and precautions which shall be employed. By mutual agreement of the parties to the test, advanced instrumentation or instrument systems, such as those using sonic devices to measure wind speed, may be used as alternatives provided that the application of such devices or systems has demonstrated an accuracy at least equivalent to that required by this Code.

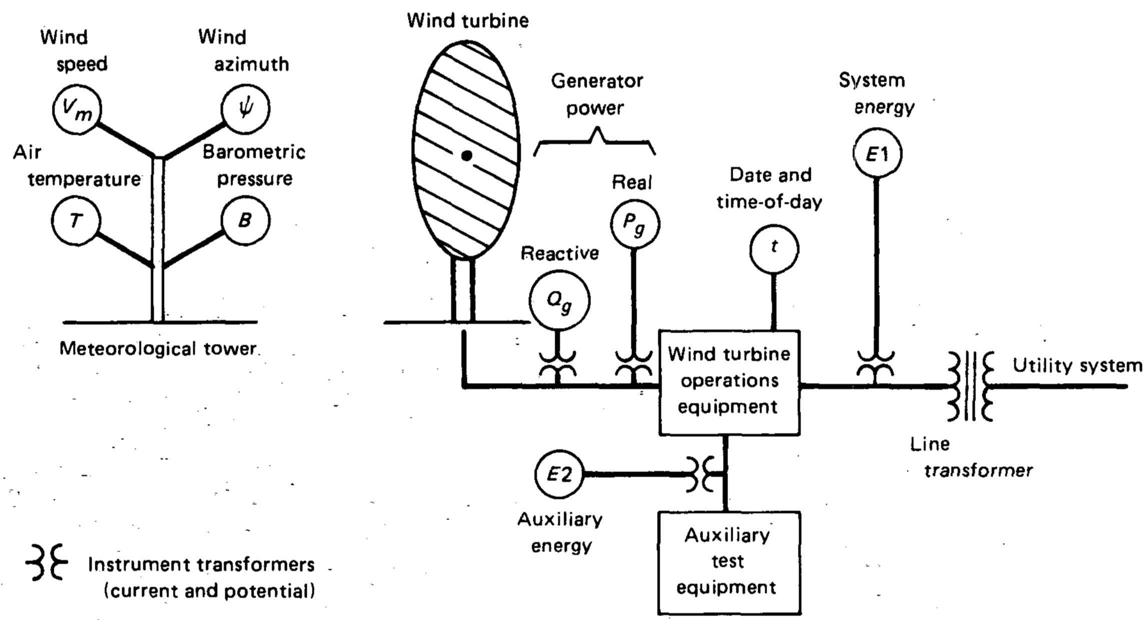


FIG. 4.1 WIND TURBINE PERFORMANCE TEST EQUIPMENT

4.2 WIND SPEED

Wind speed measurements are critical to the outcome of the WT performance test, and special precautions shall be taken to ensure proper calibration, location, installation, and maintenance of sensors and data processing equipment. Wind speed shall be measured continuously by duplicate anemometers located upwind of the WT at an elevation that will provide a representative sampling of the wind energy input to the WT, without disturbance by WT operation. Wind speed measurements are averaged over the duration of a test segment and the average wind speed is used to predict energy output. The following sections provide specific requirements for anemometer characteristics, anemometer location, and correlation of measured wind speed with undisturbed wind speed at the center of the rotor's swept area.

4.2.1 Test Anemometers. Test anemometers shall measure the horizontal component of the wind velocity and have operating ranges that extend at least 4.0 meters per second beyond the maximum wind speed required for the test. Calibration accuracy of anemometers shall be better than ±0.2 meters per second, and distance constants shall be 5 meters or less. Anemometers shall be calibrated within 3 months before and 1 month after the test. Background information on anemometry is given in Appendix B to this Code.

4.2.2 Duplicate Anemometers. Duplicate anemometers shall be used for reliability and verification of data. An average wind speed shall be obtained from each anemometer for each test segment. The measured wind speed for the test segment shall be the average of these two averages. When one anemometer average is repeatedly lower than the other by more than 3% or 0.5 meters per second, whichever is larger, this inconsistency shall be resolved prior to the next test run.

4.2.3 Anemometer Location. Anemometer location shall be on a meteorological tower in accordance with Fig. 4.2. As shown in the plan view, the meteorological tower is upwind of the WT in the prevailing wind direction. The distance *L* from the WT to the meteorological tower shall be from two to six times the rotor diameter *D*.

The elevation above ground of the center of the rotor's swept area is the reference elevation, h_0. Anemometer elevation shall be between Level A, which is h_0 above the ground at the meteorological tower, and Level B, which is at the same altitude above sea level as

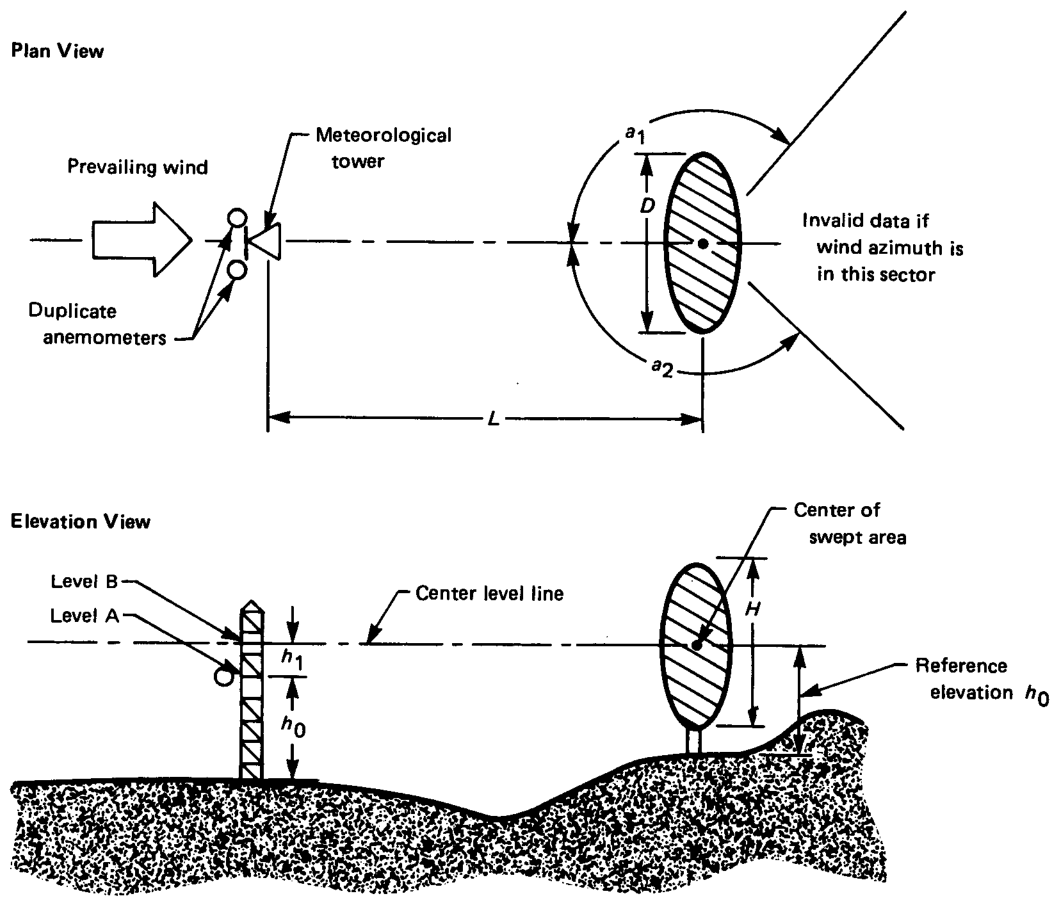


FIG. 4.2 WIND TURBINE PERFORMANCE TEST LAYOUT

the rotor center. Level A is recommended. Both anemometers shall be at the same level.

4.2.4 Wind Speed Correlation Tests. Wind speed correlation tests are normally required to determine differences, if any, between average wind speeds measured by the test anemometers, and concurrent average wind speeds near the center of the rotor's swept area, without WT interference. The scope of the correlation tests and the analysis of the results shall be agreed upon by the parties prior to the performance test. Correlation test results are expressed as adjustments to the measured wind speed that are functions of wind speed and azimuth (see para. 5.2). Wind speed correlation tests are strongly recommended but not required when the meteorological tower is less than four rotor diameters from the WT, the distance h_1 between Levels A and B (elevation view, Fig. 4.2) is less than 0.2 times the rotor height H, and the anemometers are located at Level A ± 0.05 times H.

4.3 WIND AZIMUTH (DIRECTION)

Wind azimuth shall be measured continuously by an instrument located on the meteorological tower at the same level as the test anemometers. Wind azimuth measurements are averaged over the duration of a test segment and average azimuths are used as described in para. 5.2.

4.3.1 Range. Range of the wind azimuth instrument shall be 0 deg. to 540 deg. with an accuracy of ± 3 deg. and a response consistent with the wind-speed sensors. Calibration of the wind azimuth instrument shall be conducted within 3 months before the test, with attention to alignment with true north during the test.

4.3.2 Invalid Sector. The "invalid" sector in Fig. 4.2 is established to prevent the WT wake from interfering with wind speed measurements made at the meteorological tower. Angles a_1 and a_2, which define the boundaries of the invalid sector, shall be no larger than 135 deg. each. Smaller angles may be agreed upon by the parties. For example, the "valid" sector may be restricted to the range of wind azimuths for which wind speed correlation data exist (para. 4.2.4).

4.4 AMBIENT TEMPERATURE

Ambient air temperature shall be measured at least hourly by a sensor located on the meteorological tower at a height between 5 meters above ground and the level of the test anemometers. Ambient temperature measurements shall be used to calculate air density during the test. All temperature measurements shall be carried out in accordance with accepted practices and procedures as discussed in PTC 19.3 on Temperature Measurement.

4.4.1 Minimum accuracy of ambient temperature measurements shall be $\pm 1\,^\circ$C. Calibration of the temperature instrument shall be conducted within 3 months before the test. The sensor shall be shielded from direct sunlight, precipitation, wind, and ground radiation.

4.4.2 Linear interpolation shall be used to determine ambient temperatures for test segments between readings.

4.5 AMBIENT PRESSURE

Ambient air (barometric) pressure shall be measured at least hourly by a sensor located on the meteorological tower near the ambient air temperature sensor. Ambient pressure measurements shall be used to calculate air density during the test. All pressure measurements shall be carried out in accordance with accepted practices and procedures for barometric pressure measurement, as discussed in PTC 19.2 on Pressure Measurement.

4.5.1 Minimum accuracy of ambient pressure measurements shall be ± 5 millibars. Calibration of the pressure instrument shall be conducted within 3 months before the test.

4.5.2 Linear interpolation shall be used to determine ambient pressures for test segments between readings.

4.6 SYSTEM ENERGY OUTPUT

System energy output shall be measured continuously by means of a three-phase induction or electronic watt-hour meter connected to appropriate current and potential transformers [6]. Current and potential transformers shall be located on the WT side of the line transformer connecting the WT to the load or electric distribution system, in accordance with Fig. 4.1. No unmetered loads necessary for WT operation shall be connected to the line between the system energy instrument transformers and the line transformer.

4.6.1 Procedures for Measurement. Procedures for measurement of electrical performance variables shall be based upon (1) three-phase AC interconnection between the WT and the load balanced within 5%, and (2) less than 5% total harmonic distortion in the voltage and current waveforms [7]. If these criteria are not met, instrumentation specifically designed for unbalanced and/or high distortion conditions shall be required.

4.6.2 Current and Potential Transformers. Current and potential transformers shall conform to ANSI/IEEE C57.13 and shall maintain specified accuracy up to 120% of rated generator voltage and current, when feeding all connected transducers.

4.6.3 If auxiliary energy for test equipment not necessary to WT operation is supplied from the load side of the system energy current transformers, system energy measurements represent the net energy output of the WT. If auxiliary energy is obtained as shown in Fig. 4.1, it must be separately measured and added to the system energy measurement to obtain net energy output.

4.6.4 Energy monitoring instrumentation shall have a minimum range greater than the product of the generator KVA rating and 200 hr. The minimum describable count of the watt-hour meter shall be 0.1% of the minimum range. Overall accuracy of the watt-hour meter, including associated current and potential transformers, connecting wiring and watt-hour meter shall be ±1% of the meter incremental reading for power levels greater than 20% of the generator rating and ±2% otherwise. The time constant of the watt-hour transducer shall not exceed 0.5 sec to indicate 99% of a step change.

4.6.5 Calibration of the watt-hour meter, associated transformers, and wiring shall be conducted within 1 month before and after the test.

4.7 WT AUXILIARY ENERGY

Auxiliary energy, supplied from the WT side of the current and potential transformers connected to the system energy meter and not required for WT operation, shall be measured separately and used to increase system energy output to compute the WT net electrical energy. Multiple metering shall be used if auxiliary energy is not all fed from one bus. Examples of equipment which may consume auxiliary energy are test equipment, station lights, heaters, and air conditioners.

4.7.1 Current and Potential Transformers. Current and potential transformers shall conform to ANSI/IEEE C57.13 and shall maintain specified accuracy up to 120% of the rated voltage and current of the auxiliary power system when feeding all the connected transducers.

4.7.2 Auxiliary-energy instrumentation shall have a range greater than the product of the manufacturer's forecast of maximum auxiliary KVA demand and 200 hr. The minimum describable count of the watt-hour meter shall be 0.1% of the minimum range. Overall accuracy of the watt-hour meter, including associated current and potential transformers, connecting wiring and watt-hour transducers shall be ±2%. The time constant of the watt-hour transducer shall not exceed 0.5 sec to indicate 99% of a step change.

4.7.3 Calibration of the auxiliary watt-hour meter, associated current and potential transformers, wiring, and watt-hour transducers shall be conducted within 1 month before and after the test.

4.8 GENERATOR POWER OUTPUT

Real and reactive generator power shall be measured to determine whether the WT is operating within the power-factor range specified by the manufacturer and/or agreed upon by the parties to the test. Generator power measurements may also be used as a basis for interpolation between energy measurements, to obtain test energy outputs for short test segments.

4.8.1 Current and Potential Transformers. Current and potential transformers connected to watt and var meters shall be located on the WT side of the line transformer connecting the WT to the load or electric distribution system and shall be between the WT and any auxiliary equipment (Fig. 4.1). The watt and var meters shall be located so that the length of wires to the recorder does not add more than 0.25% error. The same current and potential transformers used for measuring output energy may be used to measure power output if the watt and var transducers have sufficiently low burden and if the transducers are specified for the proper range and accuracy.

4.8.2 Range. Ranges of the real and reactive power instrumentation (including instrument transformers) shall be ±150% of the generator KVA rating. The watt transducer shall have a full-range accuracy of ±0.25% and the var transducer shall have a full-range accuracy of ±0.5%. Response time of the transducers shall not exceed 0.5 sec to indicate 99% of a step change.

4.8.3 Calibrations of power instrumentation shall be conducted within 1 month before and after the test.

4.9 DATA RECORDING AND MONITORING SYSTEMS

Transducer output data (described in paras. 4.1 to 4.7) shall be recorded for the purpose of performing data reduction, calculating performance parameters, and constructing the permanent record, as well as to provide real-time monitoring of the measured variables.

4.9.1 Data shall be recorded in or converted to digital format using 8 bits or more resolution. Variables to be recorded shall include at least the following (symbols in parentheses; see Fig. 4.1):

(a) date and time-of-day (t)
(b) system energy output ($E1$)
(c) auxiliary energy supplied by the WT ($E2$)
(d) wind speed (V_m)
(e) wind azimuth (ψ)
(f) air temperature (T)
(g) barometric pressure (B)
(h) generator power (real) (P_g)
(i) generator power (reactive) (Q_g)

4.9.2 Sampling Frequency. Sampling frequency shall be at least once per second for the following variables: date and time-of-day, wind speed, wind azimuth, generator real power, and generator reactive power. Except for date and time-of-day, these samples shall be averaged over the duration of a test segment and the averages recorded. Sampling frequency shall be at least once per hour and at the beginning and end of each test run for the following variables: system energy output, auxiliary energy, ambient temperature, and ambient pressure.

4.9.3 Data Monitoring System. Variables displayed for real-time monitoring shall include at least the following:

(a) generator power (real) (P_g)
(b) generator power (reactive) (Q_g)
(c) wind speed (V_m)
(d) wind azimuth (ψ)

SECTION 5 — CALCULATION PROCEDURES

5.1 INTRODUCTION

Recommended procedures for calculating measured test energy output, predicted test energy output, test energy ratio, test power curve, and annual energy ratio are presented in this Section. Equations are given, together with tabular forms suitable for recording reference and test data, performing calculations, and recording results.

5.1.1 Sample Test Data. Sample test data from [2] are used to illustrate the recommended calculation procedures. These data were measured during performance tests of three large, horizontal-axis wind turbines. A description of these WTs, the layout of the test site, and performance test data are all given in [8]. This sample is a composite of test data from all three of the turbines, and does not represent the performance of a specific WT.

5.1.2 Reference Data. Reference data, agreed upon prior to the start of the performance test, should be clearly documented, preferably in numerical tables which minimize ambiguity and the need for interpretation. Sample Table 5.1 lists required reference data items. Items 1 through 4 define time durations for various elements of the test. Minimum total test time and its distribution with respect to wind speed ranges are given in Items 1 and 2. The minimum duration of a test run is given in Item 3. Test runs are subdivided into test segments, whose duration is defined in Item 4.

Items 5 through 11 define the dimensional parameters in Fig. 4.2 that locate the test anemometers and the wind azimuth sector for which data are invalid. Item 12 is the reference air density selected for the test power curve. The mean test air density is recommended as a reference in order to minimize corrections to the test data. Item 13 is the range of air densities which could occur during the test and for which reference power output must be calculated. Items 14 and 15 provide guidelines for sorting the test data according to narrow wind speed ranges or "bins," for purposes of calculating a test power curve.

Items 16 through 19 refer to succeeding tables in which reference wind speed, reference power, and reference energy output data are documented. Item 16 is a tabular listing of any adjustments which must be made to the measured wind speed in order to obtain the test wind speed, accounting for topographical and other effects. Item 17 documents the reference power output as a function of wind speed, for air densities within the range given in Item 13 and for the reference air density (Item 12) if the latter is not within this range. Item 18 is the annual histogram of wind speeds required to compute annual energy outputs. Item 19 defines the reference annual energy output obtained by combining each power curve in Item 17 with the wind histogram in Item 18.

5.2 TEST WIND SPEED CORRELATION

The test wind speed is defined as the site free-stream wind speed at the reference elevation. In the general case, the measured wind speed will need adjustment in order to satisfy this definition. For example, the wind measurement station may not be at the reference elevation, topographic features may alter wind speeds from certain azimuths, and the WT wake will affect wind measurements for a range of wind azimuths. Therefore, a preliminary test to determine the correlation between measured wind speed and test wind speed is recommended and, under certain conditions (see para. 4.2.4), is required. The recommended procedure for calculating test wind speed from measured wind speed is as follows: Let

$$V_t = V_m + V_a(V_m, \psi) \qquad (1)$$

where

V_t = test wind speed, m/s
V_m = measured wind speed, m/s
V_a = wind speed adjustment, a function of measured wind speed and azimuth, m/s
ψ = measured wind azimuth, deg.

SAMPLE TABLE 5.1
REFERENCE DATA AGREED UPON BY PARTIES TO THE TEST

Reference Item	Quantity
1. Minimum test duration	20.0 h
2. Minimum duration in wind speed ranges:	
(a) Below 8.0 m/s	8.0 h
(b) From 8.0 to 14.0 m/s	8.0 h
(c) Above 14.0 m/s	4.0 h
3. Minimum test run duration	1.0 h
4. Test segment duration	0.167 h
5. Diameter of swept area of rotor	91.4 m
6. Height of swept area of rotor	91.4 m
7. Azimuths from rotor to meteorological tower	221 deg.
8. Distance from rotor to meteorological tower	303 m
9. Azimuths in wake sector (invalid data)	341-100 deg.
10. Elevation of center of swept area AGL	60.9 m
11. Elevation of anemometers AGL	59.4 m
12. Reference air density	Mean test density kg/m^3
13. Nominal range of air densities	1.03 to 1.23 kg/m^3
14. Minimum wind speed bin size	1.0 m/s
15. Minimum test energy output in bin	1.0 MWh
16. Adjustments to measured wind speed	See Sample Table 5.2
17. Reference power output	See Sample Table 5.3
18. Reference annual wind speed duration	See Sample Table 5.4
19. Reference annual energy output	See Sample Table 5.5

The preferred method for documenting the wind speed adjustment V_a is by tabulation, following the format of Sample Table 5.2. For wind directions which place the anemometer in the wake of the WT (see Fig. 4.2), test data are invalid and should be appropriately marked.

5.3 REFERENCE POWER OUTPUT, ANNUAL WIND DURATION, AND ANNUAL ENERGY

All reference data required for the prediction of test energy output and annual energy output shall be documented prior to the test. Sample Table 5.3 illustrates the recommended form of documentation of reference power output, annual wind duration, and annual energy output.

5.3.1 Reference Power Output. Reference power output at the system energy measurement point ($E1$, Fig. 4.1) must be defined as a function of both test wind speed and air density, for the range of air densities specified in Sample Table 5.1, and for the reference air density if the latter is not in this range. Reference power curves may be expressed in equation form for purposes of computation, but formal documentation should

SAMPLE TABLE 5.2
ADJUSTMENTS TO MEASURED WIND SPEED

Measured Wind Speed, V_m, m/s	Wind Speed Adjustment, V_a, m/s [Note (1)]				
	Measured Wind Azimuth, ψ, deg.				
	Wake Sector 341–100	Sector A 101–160	Sector B 161–220	Sector C 221–280	Sector D 281–340
0.0 - 4.9	Invalid	0	0	0	0
5.0 - 5.9	Invalid	0.1	0.1	0.1	0
6.0 - 6.9	Invalid	0.1	0.2	0.1	0
7.0 - 7.9	Invalid	0.2	0.3	0.2	0
8.0 - 8.9	Invalid	0.2	0.3	0.2	0
9.0 - 9.9	Invalid	0.3	0.4	0.3	0
10.0 - 10.9	Invalid	0.4	0.5	0.4	0
11.0 - 11.9	Invalid	0.4	0.5	0.4	0
12.0 - 12.9	Invalid	0.4	0.6	0.4	0
13.0 - 13.9	Invalid	0.4	0.6	0.4	0
14.0 - 14.9	Invalid	0.4	0.6	0.4	0
15.0 - 15.9	Invalid	0.4	0.5	0.4	0
16.0 - 16.9	Invalid	0.3	0.5	0.3	0
17.0 - 17.9	Invalid	0.3	0.4	0.3	0
18.0 - 18.9	Invalid	0.2	0.3	0.2	0
19.0 - 19.9	Invalid	0.2	0.2	0.2	0
20.0 - 20.9	Invalid	0.1	0.2	0.1	0
≥21.0	Invalid	0.1	0.1	0.1	0

NOTE:
(1) Added to measured wind speed V_m to obtain test wind speed V_t.

be in tabular form for clarity and for verification of computations. Sample Table 5.3 shows a format for documentating reference power output P_r as a function of test wind speed V_t and air density ϱ. Increments in this table shall be small enough to permit linear interpolation.

Some turbine control systems limit power output and, as a result, power output will be independent of air density at certain wind speeds. In Sample Table 5.3, the power limit is 2500 kW. As shown by the irregular dashed line in the table, the lowest wind speed at which the control system limits output to 2500 kW depends, to some extent, on the air density.

5.3.2 Reference Annual Histogram. A reference annual histogram of wind speeds must be defined in order to accomplish a secondary objective of the performance test, which is to compare test and predicted energy outputs on an annual basis. As shown in the left two columns of Sample Table 5.3 an annual duration Δt_a is associated with each increment of test wind speed. Durations must total 8760 hours per year. In this example, increments are 0.5 meter per second in size, and the test wind speed is at the midpoint of the increment.

Direct measurement of the annual duration of wind speeds at the reference elevation is the preferred method for obtaining the reference annual histogram of wind speeds. In the absence of annual wind test data, an analytical distribution may be used. A commonly-used distribution is the Weibull [9, 10], which contains two empirical constants that determine the annual average wind speed and the variance from that average. These two constants may be adjusted to represent the wind regime expected at the test site or a common wind regime selected as a basis for comparison of test data from several WTs. Equations defining the Weibull distribution are as follows:

$$\Delta t_a(V_1 < V_t < V_2) = 8760 \left\{ \exp\left[-(V_1/C)^k\right] - \exp\left[-(V_2/C)^k\right] \right\} \quad (2a)$$

and

$$\bar{V} = C \times \Gamma(1 + 1/k) \quad (2b)$$

where

Δt_a = annual duration of the test wind speed V_t in the range from V_1 to V_2, h/y
C = empirical scale constant, m/s
k = empirical shape constant
$\bar{V}$ = annual average wind speed, m/s
$\Gamma(\ )$ = Gamma function of ( )

In Sample Table 5.3, durations in the second column are calculated according to a Weibull distribution with a scale constant of 10 meters per second, a shape constant of 2.7, and an annual average wind speed of 8.89 meters per second.

5.3.3 Reference Annual Energy Output. Reference annual energy output is documented at the bottom of Sample Table 5.3 for each air density and its corresponding power curve. Operational availability is assumed to be 100% for purposes of comparing test and reference annual energies. Therefore, the total duration in each wind speed interval is multiplied by the corresponding average reference power to obtain the annual reference energy output for each interval ΔE_{ra}. Totaling energies for all intervals gives the reference annual energy output E_{ra} for a given air density. Thus

$$\Delta E_{ra} = \Delta t_a \times P_r \quad (3)$$

and

$$E_{ra} = \Sigma\ \Delta E_{ra} \quad (4)$$

where

ΔE_{ra} = reference annual energy output in a wind speed range, MWh
P_r = reference power output at average wind speed within the range and test air density, MW
Δt_a = annual duration in a wind speed range, h
E_{ra} = reference annual energy output, MWh

5.4 TABULATION OF MEASURED TEST DATA

Parameters measured during the performance test are described in Section 4. The recommended format for tabulating measured data and calculating measured test energy output is given in Sample Table 5.4.

5.4.1 Measured Data. Measured data are listed separately for each test run, with each run identified by a number i (running consecutively from 1 to I) and by date. Data measured during the test run are tabulated as a matrix, in which each row contains measurements for one test segment. The first item in each row is the test segment number j, which runs consecutively from 0 to J. The number 0 indicates initial conditions only. The second item in each row is the time-of-day t measured at the end of the test segment. Thus, t_0 is the end of segment 0 and the start of the test run. Similarly, time t_J is the end of segment J and the end of the run.

The third and fourth items in the row are the measured wind speed V_m and wind azimuth ψ, both averaged over the test segment. The fifth and sixth items in the row are the measured ambient air temperature T and barometric pressure B. These items of test data are listed only in the rows corresponding to the time-of-day at which temperature and pressure readings were actually taken. These readings may be as infrequent as once per hour (see para. 4.2).

System energy meter readings $E1$ and readings of any auxiliary energy meter (or meters) $E2$ are listed next in Sample Table 5.4. System meter readings are recorded at the end of each test segment starting with segment zero. Energy meter readings are listed only in the rows corresponding to the time of day at which the meter was actually read. These readings may be as infrequent as once per hour (see para. 4.3). The number of test segments which constitute a test run must be selected so that readings of the energy meters are available for the start and finish of the run.

The ninth column in Sample Table 5.4 lists measurements of generator power P_g averaged over the test segment. The main use of these power measurements is for interpolation between system energy meter readings in order to define a test power curve. Generator power measurements are not required for the calculation of the Test Energy Ratio. If system energy can be metered directly for each test segment, then the test power curve can be obtained without generator power data. However, power measurements are still recommended as a supplement to the energy meter data and for the validation of proper system operation.

5.4.2 Measured Test Energy. Measured test energy for each test segment dE_m is listed in the last column in

SAMPLE TABLE 5.3
REFERENCE POWER OUTPUT, REFERENCE ANNUAL WIND DURATION, AND REFERENCE ANNUAL ENERGY OUTPUT

Test Wind Speed, V_t, m/s	Reference Annual Duration [Note (1)], Δt_a, h/y	Reference Power Output, P_r, kW, Determined From Test Wind Speed and Air Density — Test Air Density, ϱ, kg/m^3 [Note (2)]: 1.03	1.05	1.07	1.09	1.11	1.13	1.15	1.17	1.19	1.21	1.23
0 - 6.2	2147	0	0	0	0	0	0	0	0	0	0	0
6.5	416	145	150	155	160	165	170	175	180	185	190	195
7	440	272	279	287	295	302	310	318	325	333	341	348
7.5	458	399	409	419	430	440	450	460	470	481	491	501
8	468	526	539	552	564	577	590	603	616	628	641	654
8.5	470	653	668	684	699	715	730	745	761	776	792	807
9	466	835	854	873	892	911	930	949	968	987	1006	1025
9.5	453	1016	1039	1062	1084	1107	1130	1153	1176	1198	1221	1244
10	435	1161	1187	1213	1239	1264	1290	1316	1341	1367	1393	1419
10.5	410	1307	1335	1364	1393	1421	1450	1479	1507	1536	1565	1593
11	381	1452	1483	1515	1547	1578	1610	1642	1673	1705	1737	1768
11.5	349	1597	1632	1666	1701	1735	1770	1805	1839	1874	1908	1943
12	314	1742	1780	1817	1855	1892	1930	1968	2005	2043	2080	2118
12.5	278	1878	1919	1959	1999	2040	2080	2120	2161	2201	2241	2282
13	242	2005	2048	2091	2134	2177	2220	2263	2306	2349	2392	2435
13.5	208	2114	2159	2205	2250	2295	2340	2385	2430	2475	2500	2500
14	175	2232	2280	2327	2375	2422	2470	2500	2500	2500	2500	2500
14.5	146	2477	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
15	119	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
15.5	95	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
16	75	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
16.5	58	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
17	44	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
17.5	33	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
18	24	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
18.5	17	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
19	12	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
19.5	9	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
20	6	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
20.5	4	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
21	3	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
21.5	2	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
22	1	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
>22.4	2	0	0	0	0	0	0	0	0	0	0	0
Total:	8760											
Ref. annual energy E_{ra}, MWh/y		7920	8064	8205	8346	8487	8628	8765	8898	9030	9159	9282

NOTES:
(1) Weibull wind distribution, with $C = 10.0$ m/s and $k = 2.7$
(2) No air density adjustment for wind speed/air density combinations below dashed line.

SAMPLE TABLE 5.4
MEASURED TEST RUN DATA AND CALCULATION OF MEASURED TEST ENERGY OUTPUT

(a) Test Run Number: $i = 1$ Date: ________

Test Segment Number, j	Time-of-Day, t, h:m	Measured Wind Speed, V_m, m/s	Wind Azimuth, ψ, deg.	Air Temp., T, °C	Barometric Pressure, B, mbar	System Energy Meter, $E1$, kWh	Aux. Energy Meter, $E2$, kWh	Measured Generator Power, P_g, kW	Measured Test Energy, dE_m, kWh
0	1610	NA	NA	29	927	1107	20	NA	NA
1	1620	6.5	283	...	...	...	...	427	39
2	1630	6.1	275	...	...	...	...	633	58
3	1640	7.2	262	...	...	...	...	581	54
4	1650	7.1	258	...	...	...	...	695	64
5	1700	7.7	251	...	...	...	...	581	54
6	1710	7.7	242	27	928	1494	27	1355	125
7	1720	7.5	242	...	...	...	...	757	70
8	1730	7.5	234	...	...	...	...	788	73
9	1740	7.2	219	...	...	...	...	726	67
10	1750	7.2	204	...	...	...	...	777	72
11	1800	7.2	193	...	...	...	...	880	81
12	1810	7.0	185	25	928	1906	34	602	56
13	1820	6.9	183	...	...	...	...	561	51
14	1830	6.5	183	...	...	...	...	365	33
15	1840	6.5	181	...	...	...	...	602	55
16	1850	6.9	179	...	...	...	...	736	67
17	1900	6.9	179	...	...	...	...	365	33
18	1910	6.9	178	22	925	2216	41	849	77
Totals:	0300					1109	21		1130
	Δt					$\Delta E1$	$\Delta E2$		ΔE_m

Sample Table 5.4, calculated according to the following equation:

$$dE_{m,j} = E1_j - E1_{j-1} + E2_j - E2_{j-1}$$

$$j = 1,...J \qquad (5)$$

where

dE_m = net test energy output measured during segment, kWh

$E1$ = system energy meter reading (output), kWh

$E2$ = auxiliary energy meter reading (load), kWh

If interpolation between energy meter readings is required in order to obtain segment energy output, the following procedure shall be used: let two consecutive readings of the energy meters be taken at the end of test segments with indices a and b. Then

$$dE_{m,j} = P_{g,j}\frac{E1_b - E1_a}{P_s} + \frac{E2_b - E2_a}{b - a}$$

$$j = a + 1,...b \qquad (6a)$$

where

$$P_s = \Sigma P_{g,j}$$

$$j = a + 1,...b \qquad (6b)$$

Thus, system energy is distributed in proportion to generator power and auxiliary energy is distributed equally to all test segments between meter readings. In Sample Table 5.4, the measured test segment energies in the last column were calculated using Eqs. (6a) and (6b).

The following summary calculations for run i complete Table 5.4:

$$\Delta t_i = t_J - t_0 \quad (7)$$

$$\Delta E1_i = E1_J - E1_0 \quad (8)$$

$$\Delta E2_i = E2_J - E2_0 \quad (9)$$

$$\Delta E_{m,i} = \Sigma \, dE_{m,j} \qquad j = 1,...J \quad (10)$$

and, for checking of calculations,

$$\Delta E_{m,i} = \Delta E1_i + \Delta E2_i \quad (11)$$

where

i = run index
Δt = duration of run, h
$\Delta E1$ = system energy output during run, kWh
$\Delta E2$ = auxiliary energy used during run, kWh
ΔE_m = net test energy output measured during run, kWh

5.5 CALCULATION OF PREDICTED TEST ENERGY OUTPUT

Sample Table 5.5 illustrates the recommended procedure for calculating the predicted test energy for each test run. Each row in this table contains data for one test segment. The first item in each row is the test segment number j, which corresponds to the segment number in Table 5.4. The second item in each row is the duration of the test segment dt, which is calculated as follows:

$$dt_j = t_j - t_{j-1} \qquad j = 1,...J \quad (12)$$

in which t, the time-of-day, is obtained from Table 5.4, and J is the total number of segments in the run. The third item in the row is the test wind speed V_t, which is calculated by means of Eq. (1). Measured wind speed and azimuth from Sample Table 5.4 and wind speed adjustments from Sample Table 5.2 are used in this calculation. Test air density ϱ is the fourth item in each row and is calculated from ambient air data in Sample Table 5.4, using the following equation:

$$\varrho = 1.226 \frac{282.2}{T + 273} \times \frac{B}{1013} = 0.3485 \frac{B}{T + 273} \quad (13)$$

where

ϱ = air density, kg/m^3
B = barometric pressure, mbar
T = air temperature, °C

If required, linear interpolation may be used to obtain air temperature and barometric pressure data for test segments intermediate between readings.

Next, the reference power output P_r is selected from Sample Table 5.3 on the basis of the test wind speed and the test air density during the segment. Interpolation between entries in the table shall be linear. The sixth and last item in each row is the predicted test energy dE_p, which is calculated for test segment j according to the following equation:

$$dE_{p,j} = dt_j \times P_{r,j} \qquad j = 1,...J \quad (14)$$

Finally, the second and sixth columns of data are summed to obtain the run duration Δt_i (for checking purposes), and the net test energy output predicted for the run $\Delta E_{p,i}$, as follows:

$$\Delta t_i = \Sigma \, dt_j \qquad j = 1,...J \quad (15)$$

and

$$\Delta E_{p,i} = \Sigma \, dE_{p,j} \qquad j = 1,...J \quad (16)$$

5.6 CALCULATION OF TEST ENERGY RATIO

The primary output of the performance test is the Test Energy Ratio, which is the ratio of the measured test energy output to the predicted energy output for the wind speed history during the test. Sample Table 5.6 is the recommended format for documenting the calculation of the Test Energy Ratio. Each row in the table summarizes the results of one test run, including the run number i, duration Δt, predicted test energy ΔE_P, measured system energy $\Delta E1$, measured auxiliary energy $\Delta E2$, and measured test energy ΔE_m.

Run data are then totaled as follows:

$$D_t = \Sigma \, \Delta t_i \qquad i = 1,...I \quad (17)$$

$$E_p = \Sigma \, \Delta E_{p,i} \quad (18)$$

SAMPLE TABLE 5.5
CALCULATION OF PREDICTED TEST ENERGY OUTPUT

(a) Test Run Number: $i = 1$ Date: ________________

Test Segment Number, j	Duration of Segment, dt, h	Test Wind Speed, V_t, m/s	Test Air Density, ϱ, kg/m^3	Ref. Power Output, P_r, kW	Pred. Test Energy, dE_p, kWh
0	NA	NA	1.07	NA	NA
1	0.167	6.5	1.07	155	26
2	0.167	6.2	1.07	0	0
3	0.167	7.4	1.07	393	66
4	0.167	7.3	1.08	371	62
5	0.167	7.9	1.08	531	89
6	0.167	7.9	1.08	531	89
7	0.167	7.7	1.08	478	80
8	0.167	7.7	1.08	478	80
9	0.167	7.5	1.08	424	71
10	0.167	7.5	1.09	430	72
11	0.167	7.5	1.09	430	72
12	0.167	7.2	1.09	349	58
13	0.167	7.1	1.09	322	54
14	0.167	6.7	1.09	214	36
15	0.167	6.7	1.09	214	36
16	0.167	7.2	1.09	349	58
17	0.167	7.2	1.09	349	58
18	0.167	7.2	1.09	349	58
Totals:	3.0 Δt				1061 ΔE_p

$$E1 = \Sigma\, \Delta E1_i \tag{19}$$

$$E2 = \Sigma\, \Delta E2_i \tag{20}$$

$$E_m = \Sigma\, \Delta E_{m,i} = E1 + E2 \tag{21}$$

Finally, the Test Energy Ratio (TER) is calculated:

$$\text{TER} = \frac{E_m}{E_p} \tag{22}$$

This completes the calculation of the primary result of the performance test.

5.7 CALCULATION OF TEST POWER CURVE

The test power curve defines the relationship between net test power output and test wind speed, at the reference air density. The procedure for obtaining a test power curve from measured data consists of three calculations: (1) calculation of bin test data, adapting procedures developed in [4] and [11]; (2) calculation of test power data points; and (3) curve-fitting of the test power data points. These calculations are discussed in the following paragraphs.

5.7.1 Calculation of Bin Test Data. Calculation of bin test data begins with sorting of performance test data according to test wind speed. Data are sorted into bins, or narrow ranges of wind speed, as illustrated by Sample Table 5.7. Each wind speed bin is labeled with a number k, running consecutively from 1 to K, and with

SAMPLE TABLE 5.6
CALCULATION OF TEST ENERGY RATIO

Test Run Number, i	Duration of Run, Δt, h	Predicted Test Energy, ΔE_p, kWh	Measured System Energy, $\Delta E1$, kWh	Measured Auxiliary Energy, $\Delta E2$, kWh	Measured Test Energy, ΔE_m, kWh
1	3.00	1061	1109	21	1130
2	5.00	4778	4624	27	4651
3	3.50	6678	6487	18	6505
4	4.50	6963	6758	22	6780
5	6.33	15642	15827	38	15865
Totals:	22.33	35122	34805	126	34931
	D_t	E_p	$E1$	$E2$	E_m

Test Energy Ratio: TER $= E_m/E_p =$ 0.995

SAMPLE TABLE 5.7
CALCULATION OF BIN TEST DATA

(a) Wind Bin No.: $k = 4$ $V_t = 10.0$ to 10.9 m/s

Test Run/Segment Numbers, i/j	Duration of Segment, dt, h	Test Wind Speed, V_t, m/s	Test Air Density, ϱ, kg/m^3	Measured Test Energy, [Note (1)], dE_m, kWh	Adjusted Test Energy, [Note (2)], dE_t, kWh
2/19	0.167	10.2	1.09	67	72
2/21	0.167	10.4	1.09	228	242
2/22	0.167	10.5	1.08	233	250
2/23	0.167	10.4	1.08	227	244
2/24	0.167	10.5	1.08	227	244
2/25	0.167	10.7	1.08	228	245
2/26	0.167	10.6	1.08	201	216
2/27	0.167	10.5	1.08	221	237
2/28	0.167	10.5	1.08	233	250
2/29	0.167	10.3	1.08	213	229
2/30	0.167	10.2	1.08	207	222
3/10	0.167	10.9	1.18	253	246
3/11	0.167	10.9	1.18	269	261
4/13	0.167	10.0	1.18	216	210
4/14	0.167	10.0	1.18	226	220
4/15	0.167	10.0	1.18	232	225
4/16	0.167	10.1	1.18	261	254
Summary:	2.839	10.4		3742	3865
	Δt	Mean, V_b		ΔE_{mb}	ΔE_{tb}

NOTES:
(1) At test air density
(2) Adjusted to reference air density of 1.15 kg/m^3

the wind speed range. Each row in this table contains data for one test segment. The first five numbers in the row are obtained directly from Sample Tables 5.4 and 5.5, by sorting on test wind speed. The sixth number in each row is the segment test energy dE_t adjusted to the reference air density ϱ_r in accordance with the following equation:

$$dE_t = dE_m \times \frac{P_r(V_t,\varrho_r)}{P_r(V_t,\varrho_t)} \quad (23)$$

where

dE_t = adjusted test energy output during segment, kWh

$P_r(V_t,\varrho_r)$ = reference power at the test wind speed and the reference air density, kW

$P_r(V_t,\varrho_t)$ = reference power at the test wind speed and the test air density, kW

Reference powers are obtained from Sample Table 5.3, using linear interpolation, if required.

Bin test data are then calculated, as follows:

$$\Delta t_{b,k} = \Sigma\, dt_{i/j} \quad (24)$$

and

$$V_{b,k} = \frac{(V_t \times dt)_{i/j}}{\Delta t_{b,k}} \quad (25)$$

$$\Delta E_{mb,k} = \Sigma\, dE_{m,i/j} \quad (26)$$

and

$$\Delta E_{tb,k} = \Sigma\, dE_{t,i/j} \quad (27)$$

in which the summations include all combinations of the run index i and the segment index j in Sample Table 5.7, and

where

k = bin index

Δt_b = bin cumulative test time, h

V_b = bin mean wind speed, m/s

ΔE_{mb} = bin cumulative measured energy output (at test air densities), kWh

ΔE_{tb} = bin cumulative adjusted test energy output (at reference air density), kWh

5.7.2 Calculation of Test Power Data Points. Calculation of test power data points, which relate test power output to test wind speed, is the second step in obtaining a test power curve. The recommended procedure for this step results in one test data point for each wind speed bin, as illustrated in Sample Table 5.8. Each line in this table contains data for one bin and is identified by the bin number k as the first item in the row. The second through fifth items are obtained directly from the bin summaries in Sample Table 5.7. The test power output for each bin P_{tb}, at the bin's average wind speed and the reference air density, is then calculated as follows:

$$P_{tb,k} = \frac{\Delta E_{tb,k}}{\Delta t_{b,k}} \qquad k = 1,...K \quad (28)$$

5.7.3 Curve-Fitting of Test Power Output Data. Curve-fitting of test power output data may now be used to obtain a continuous curve of test power output versus reference wind speed. The form of the fitted curve or curve segments most appropriate for the test data must be agreed upon by the parties to the test after graphing the data in columns 3 and 6 of Sample Table 5.8. The fitted curve may be extrapolated beyond the wind speed range of the test data, to lower or higher wind speeds, by agreement of the parties on the mathematical form and range of the extrapolation.

Figure 5.1 illustrates typical power curve data, including the reference power curve, the test power data points (one for each wind speed bin), and the test power curve, fitted to the data points. The air density for all data in this figure shall be the reference air density.

The recommended method for documenting the test power curve is by means of a table which contains data for wind speeds identical to those in Sample Table 5.3. This is shown in Sample Table 5.9, in which test power output is tabulated in the third column versus wind speed listed in the first column. Test power in this table is obtained from the curve-fit of the test data (Fig. 5.1) and is not necessarily the same as the test power data points for individual wind speed bins.

5.8 CALCULATION OF ANNUAL ENERGY RATIO

The third and final result of the performance test is the Annual Energy Ratio, which compares test energy output to reference energy output on the basis of an annual wind histogram, rather than the test wind histogram. The recommended procedure for calculating and documenting this ratio is shown in Sample Table 5.9. The format of this table is similar to that of Sample

SAMPLE TABLE 5.8
CALCULATION OF TEST POWER CURVE DATA

Wind Bin Number, k	Duration of Bin, Δt_b, h	Test Wind Speed (mean), V_b, m/s	Measured Test Energy, [Note (1)], ΔE_{mb}, kWh	Adjusted Test Energy, [Note (2)], ΔE_{tb}, kWh	Test Power Output, [Note (2)], P_{tb}, kW
1	3.83	7.3	1590	1790	457
2	1.83	8.4	1240	1301	711
3	2.50	9.5	2640	2625	1050
4	2.83	10.4	3742	3865	1366
5	2.50	11.3	4184	4075	1630
6	2.67	12.6	5999	5847	2190
7	0.83	13.3	1922	1910	2301
8	1.67	14.4	4186	4186	2507
9	1.00	15.5	2580	2580	2580
10	1.67	17.0	4305	4305	2578
11	1.00	20.0	2543	2543	2543
Summary:	22.33	11.5	34931	34987	
	D_t	Mean	E_m	E_t	

NOTES:
(1) At test air density
(2) Adjusted to reference air density of 1.15 kg/m^3

Table 5.3 which was used previously for the calculation of the reference annual energy output. The test wind speeds V_t and annual durations Δt in Sample Table 5.9 must be identical to the corresponding entries in Table 5.3. The test power output data in the third column of Sample Table 5.9 document the test power curve in Fig. 5.1. Test energy outputs for each wind speed range and for a reference year are then calculated as follows:

$$\Delta E_{ta} = \Delta t_a \times P_t \tag{29}$$

and

$$E_{ta} = \Sigma \, \Delta E_{ta} \tag{30}$$

where

ΔE_{ta} = test annual energy output in a wind speed range, MWh

P_t = test power output at average wind speed in range and reference air density, MW

Δt_a = annual duration in a wind speed range, h

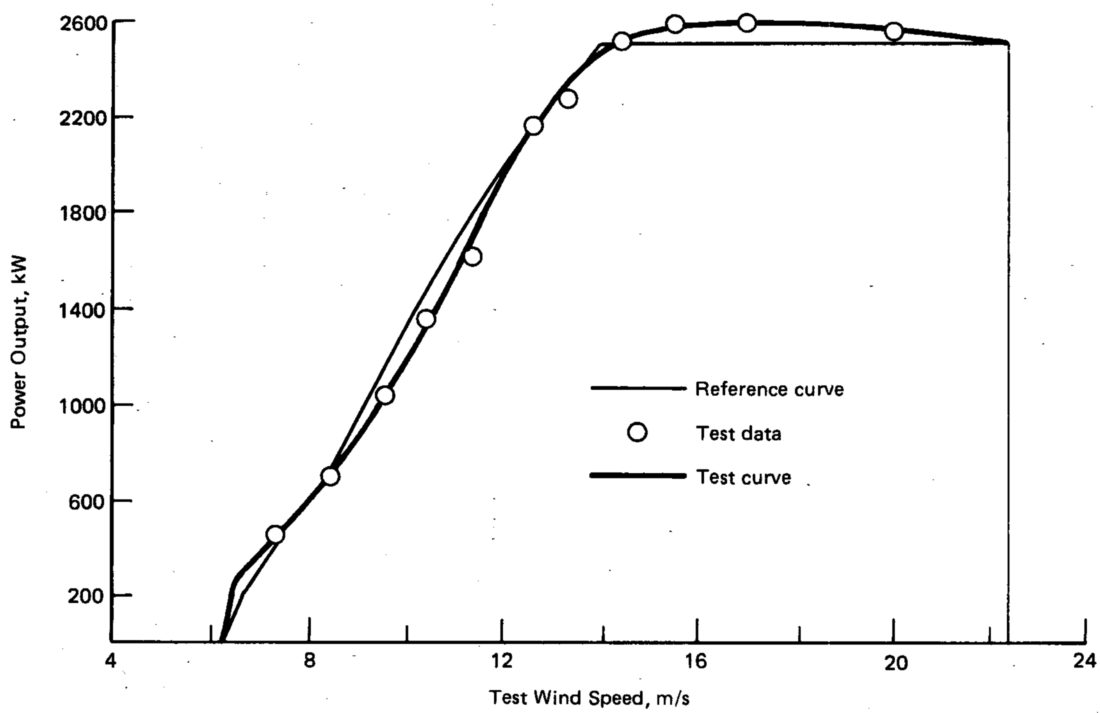
E_{ta} = test annual energy output, MWh

The Annual Energy Ratio (AER) is then given by the following:

$$\text{AER} = \frac{E_{ta}}{E_{ra}} \tag{31}$$

in which the reference annual energy output E_{ra} is obtained from Sample Table 5.3 for the reference air density.

The difference between the Test Energy Ratio value 0.995 and the Annual Energy Ratio value 0.984 results from distribution differences between the test wind speed histogram and the reference annual wind speed histogram.



Air density = 1.15 kg/m^3
(Ref. test air density)

FIG. 5.1 SAMPLE POWER CURVES AND TEST DATA

SAMPLE TABLE 5.9
TEST POWER CURVE AND CALCULATION OF ANNUAL ENERGY RATIO

Test Wind Speed, V_t, m/s	Reference Annual Duration, Δt, h/y	Test Power Output, [Note (1)], P_t, kW	Test Annual Energy, [Note (1)], ΔE_{ta}, MWh/y	Reference Power Output, [Note (1)], P_r, kW	Reference Annual Energy, [Note (1)] ΔE_{ra}, MWh/y
0 - 6.2	2147	0	0	0	0
6.5	416	274	114	175	73
7	440	385	170	318	140
7.5	458	497	227	460	211
8	468	613	287	603	282
8.5	470	734	345	745	351
9	466	881	410	949	442
9.5	453	1042	473	1153	523
10	435	1204	524	1316	572
10.5	410	1376	565	1479	607
11	381	1553	592	1642	626
11.5	349	1730	603	1805	629
12	314	1912	600	1968	618
12.5	278	2094	582	2120	590
13	242	2261	548	2263	549
13.5	208	2387	496	2385	496
14	175	2470	433	2500	439
14.5	146	2520	367	2500	364
15	119	2555	304	2500	297
15.5	95	2575	245	2500	238
16	75	2580	194	2500	188
16.5	58	2580	150	2500	145
17	44	2580	114	2500	111
17.5	33	2580	85	2500	83
18	24	2580	63	2500	61
18.5	17	2575	45	2500	44
19	12	2565	32	2500	31
19.5	9	2555	22	2500	21
20	6	2545	15	2500	15
20.5	4	2535	10	2500	10
21	3	2525	6	2500	6
21.5	2	2515	4	2500	4
22	1	2505	3	2500	3
>22.4	2	0	0	0	0
Totals:	8760		8628 E_{ta}		8765 E_{ra}

Annual Energy Ratio: AER = E_{ta}/E_{ra} = **0.984**

NOTE:
(1) At reference air density of 1.15 kg/m^3

SECTION 6 — REPORT OF TEST

6.1 GENERAL INFORMATION

6.1.1 Purpose. The report of test shall be prepared to formally document the observed data and computed results. It shall contain sufficient information to prove that all Code test objectives were attained.

6.1.2 Contents. Parts I to VI shall be included in the Report of Test, as listed below:

(a) Part I — General Information
(b) Part II — Summary of Test Results
(c) Part III — Description of Wind Turbine Tested
(d) Part IV — Observed Data and Computed Results
(e) Part V — Test Methods and Procedures
(f) Part VI — Supporting Data

6.2 DETAILED INFORMATION

The following is a discussion of each part of the test report.

6.2.1 Part I — General Information. This part shall include the following items:

(a) date(s) of test
(b) parties to the test and designated representatives
(c) test object
(d) location of test facilities
(e) WT manufacturer's name
(f) serial number and complete identification of the WT
(g) summary statement of test conditions
(h) test manager

6.2.2 Part II — Summary of Test Results. This part shall include those quantities and characteristics which describe the performance of the WT at test conditions. The Test Report Form for the particular test shall list the quantities, characteristics, and units of measurement required for the report.

6.2.3 Part III — Description of Wind Turbine Tested. This part may include assembly drawings, manufacturing drawings, and measured dimensions if agreed to by the Parties to the test. If no agreement is made, then it shall contain such descriptive information as may be furnished by the manufacturer or from catalogs.

6.2.4 Part IV — Observed Data and Computed Results. This part shall include a record of data and calculations required to determine the results of the tests. The data shall have been corrected for instrument calibrations and conditions prevailing for each test run. Calculation procedures described in Section 5 are to be used in computing test results. The computation forms included in Sample Tables 5.1 to 5.9 shall be used for documenting test results. Analysis of uncertainty in the test results shall also be included in this part of the report.

6.2.5 Part V — Test Methods and Procedures. This part shall include a detailed description of the instruments and apparatus used and procedures for observing the characteristics of the WT during test.

A sketch similar to Fig. 4.1 shall be included to show the location of major equipment and instruments. A dimensioned sketch similar to Fig. 4.2 shall be included with indications of any major topographic features within 1 mile which may significantly affect wind behavior.

6.2.6 Part VI — Supporting Data. This part shall include pertinent material supplementary to the data presented elsewhere in the Report of Test. This material may include, but not necessarily be limited to, the following:

(a) instrument calibration records;
(b) detailed log sheets;
(c) typical test data records;
(d) sample calculations.

SECTION 7 — MEASUREMENT UNCERTAINTY

7.0 TOTAL UNCERTAINTY

In order to qualify as a Code test, the total uncertainty of any individual test measurement, averaged over a test segment and calculated by the procedures specified in PTC 19.1-1985 [12] and this Code, must be less than ±2% of full scale. The results of the test are those calculated directly from the measured values employing instrumentation recommended in this document, corrected only for instrument calibration and deviation from specified operating conditions.

7.1 UNCERTAINTY ANALYSIS

Uncertainty in the Test Energy Ratio, the primary result of a Code WT test, shall be calculated in accordance with the procedures provided in PTC 19.1-1985 [12] and the results included in the Report of Test.

7.2 SOURCES OF UNCERTAINTY

Wind speed measurements are the principal contributors to uncertainty in WT performance tests [13]. Factors which can cause uncertainty in the test wind speed are:

(a) anemometer instrument errors;

(b) measuring wind speed at a point rather than over an area;

(c) separation between the anemometer and the WT;

(d) topography effects; and

(e) wind turbulence.

Other sources of uncertainty specifically related to a WT performance test are:

(f) condition of the rotor blade surfaces;

(g) operation of the WT control system; and

(h) precipitation.

7.3 PROPAGATION UNCERTAINTY

Because wind speed measurements are made at a location separated from the operating WT, propagation uncertainties in excess of ±2% of full scale may exist. However, propagation uncertainties are associated with use of the measured data and not with the measurements themselves. The methodology established by this Code (for example, para. 4.2.4) serves to minimize the impact of propagation uncertainties on performance test results.

7.4 TOLERANCE

Tolerances are not considered in this Code (see para. 3.18). Uncertainty shall not be interpreted as a tolerance on performance.

APPENDIX A
ANEMOMETRY

(This Appendix is not a part of ASME/ANSI PTC 42-1988.)

A.1 TYPES OF ANEMOMETERS

Anemometers may be classified into the following major categories:

(a) momentum transfer: cups, propellers, and pressure plates;

(b) pressure on stationary sensor: pitot tubes and drag spheres;

(c) heat transfer: hot wires and hot films;

(d) Doppler techniques: acoustic and laser;

(e) special methods: ion displacement, vortex shedding, etc.

For use in conjunction with wind turbine performance tests, the momentum transfer sensors (specifically the rotation types) are currently used more often than other types of anemometers. All types have various limitations that can be related to factors of accuracy, response, range, complexity, cost, operating environment limitations, or maintainability. Two surveys of currently available wind-measuring instrumentation have been made [14 and 15] which provide information on principles of operation, specifications, and expected performance. Useful information is also available in [16].

The following discussion of types of anemometers and their features is taken from [17]:

> For the measurement of horizontal winds, the most commonly used sensors are the cup and vane, and the propeller and vane. For horizontal and vertical winds, the most common sensors are cup and vane plus vertical axis propeller, propeller and vane with added vertical degree of freedom (bivane), and three component propellers (uvw anemometer). For speed or component measurements, either the cup or propeller anemometer has certain desirable features:
>
> 1. Linearity between wind speed and sensor output over a wide speed range.
>
> 2. Wind speed indications unaffected by changes in air density, temperature, humidity or pressure.
>
> 3. Relatively long-term calibration stability.
>
> 4. Easily adaptable to remote electronic data recording.
>
> 5. Generally require relatively little maintenance.
>
> For general review of anemometers and other meteorological instrumentation, see Hewson (1968), Modes (1968), and Middleton and Spilhaus (1953).
>
> Cup and propeller anemometers consist of two sub-assemblies: A rotor and a signal generator. In well-designed systems, the angular rotation rate of the rotor varies linearly with the wind speed. Near the starting threshold, however, substantial deviations from linearity may occur.

Since starting thresholds are well below the WT turbine cut-in wind speeds, these deviations should not present any problems during performance tests. Furthermore, in the case of a propeller anemometer, rotation rate varies linearly with the wind speed component parallel to the propeller axis.

A.2 CHARACTERISTICS OF CUP AND PROPELLER ANEMOMETERS

Cup and propeller anemometers differ in their aerodynamic characteristics. Cup types are drag devices which are not influenced by wind azimuth. Propeller types are lift devices which can be influenced by off-axis winds, resulting in an output which is approximately proportional to the square of the cosine of the orientation error. Further information on the characteristics of cup and propeller anemometers is provided in [17], as follows:

Cup anemometers are generally used in a three or four cup configuration, although specialized two-level "staggered" six-cup anemometers have been developed (Lindley, 1975). Cups of 90 degrees, with a rounded-tip conical shape, have the advantage of reduced overspeed, especially if the cups are "beaded" or have a small lip construction (Frenzen, 1967). Propellers of the four blade type have some advantages over two bladed designs in starting threshold and smoothness of response.

Since both cup and propeller rotors turn at angular rates proportional to wind speed, they are particularly convenient for driving a wide variety of signal generators. Popular methods of signal generation are AC generator, DC generator, optical or magnetic pulse generators, and dials or registers that count turns of the rotor head. The choice of signal generator is largely a matter of the type of data logger and recorder system to be used.

NOTE: A digital counting scheme is generally preferred because it eliminates problems caused by long-term voltage drift and line losses associated with analog electronics.

The transient response of cup or propeller anemometers can be characterized by a distance constant L (which is equivalent to a time constant which varies inversely with the true wind speed U). This makes the time constant shorter in high true winds and longer in low true winds, and, as a result, the anemometer accelerates faster than it decelerates. This behavior leads to over-estimation of wind speed (overspeed or "u-error"; see para. A.3.1). The distance constant for an anemometer is that passage of wind required for the output to indicate 63 percent of a step function change in wind speed. With exponential behavior, 95 percent indication would be achieved in a wind run equal to three distance constants. Distance constants for anemometers range from less than 1 meter for research instruments to 2-5 meters for adequately designed operational instruments.

Further information on the subject of distance constants of anemometers, taken from [18], follows:

The distance constant is a characteristic of cup and propeller anemometers and is essentially fixed for a given anemometer for acceleration unless the air density changes or large variations of speed cause the cups to experience a change of drag coefficient.

For a cup anemometer, if I is polar moment of inertia of the cup rotor, ϱ the air density, r the distance between the rotor axis and the center of the cups, C the effective drag coefficient of the cups, and A the cup area normal to the wind, then the distance constant, L, can be expressed by

$$L = \frac{I}{\varrho r^2 CA} \qquad (A.1)$$

L is therefore a characteristic proportional to the inertia of the anemometer. It indicates how well the anemometer responds to changes of wind speeds. An anemometer with a small distance constant will detect rapid changes accurately; conversely, an anemometer with a large L will ignore rapid changes and will tend to lag in its response.

In turbulent winds, cup anemometers tend to "overspeed" and propeller anemometers tend to "underspeed," due to their lagging response.

Research grade cup anemometers may typically overspeed the actual wind speeds by up to one to two percent. Propeller anemometers may also underspeed when not directly oriented in turbulent winds. Reference [19] provides detailed discussions of the behavior of various types of anemometers during unsteady wind conditions.

A.3 ANEMOMETRY ERRORS

A.3.1 Errors in True Wind Speed. Anemometers are subject to a variety of errors in the determination of true wind speed. In [17] these errors are summarized as follows:

If $\overline{U}$ is the true horizontal mean wind speed along the average wind azimuth line and U_i is the indicated wind speed, then, from MacCready (1966),

$$\overline{U} = \overline{U}_i (1 - e_u)(1 + e_v) \times (1 - e_w)(1 - e_{dp}) \qquad (A.2)$$

where the "u-error", e_u; "v-error", e_v; and "w-error", e_w; are related to the turbulence response characteristics of the sensor. The "data processing error", e_{dp}, is due to totalizing wind along the "instantaneous" direction rather than the resultant direction over the averaging interval (e.g., a test segment). The e_u, e_v, and e_w error designations are based on u being along the mean wind direction, v being horizontal and perpendicular to u, and w being vertical.

Figure A.1 illustrates these error components. Error components are different for cup and propeller anemometers because of their differing aerodynamic characteristics.

Reference [17] provides equations which may be used to estimate the size of these errors.

A.3.2 Error in Indicated Wind Speed. When cup or propeller anemometers are used, mean wind speeds and wind "runs" are computed by counting the number of rotor rotations in a given amount of time. Ideally, these can be expressed by

$$U_i = b\omega \qquad \text{(A.3)}$$

where U_i is the indicated wind speed, b is a calibration factor, and ω is the rotational speed of the anemometer. However, calibration tests performed in wind tunnels have shown that most anemometers respond to

$$U_i = a + b\omega \qquad \text{(A.4)}$$

where a is a second correction factor reflecting the friction losses in the anemometer [20].

Investigators at the Battelle Pacific Northwest Laboratory (PNL) and Michigan State University have found that cup anemometers with small distance constants are subject to errors induced by bearing wear after several months of operation. The bearings should, therefore, be replaced before the initial calibration of the anemometer prior to the performance test.

A.4 CALIBRATION OF ANEMOMETERS

The important subject of anemometer calibration is discussed in [17], from which the following is taken:

> Early investigators found that linear calibration occurred when the ratio of anemometer arm length to cup radius, l/r, was kept near 2.5 (Sheppard, 1940; Middleton and Spilhaus, 1953). Recently Lindley (1975) found very little sensitivity of calibration linearity to l/r between values of 1.5 and 3. Slight improvements in linearity and slight minima in distance constants were found by Lindley within the l/r range of approximately 2 to 3. Thus, the l/r of about 2.5 which prevails in most commercial instruments seems generally at or near optimum.
>
> Before use and periodically (e.g., once per year) during operation, an anemometer sensor and indicating system should be calibrated in a wind tunnel. This is done by observing indicated speed against known true wind tunnel speed and evaluating the best-fit linear relationship between the two, in accordance with Eq. (A.4).
>
> The threshold starting speed is difficult to determine accurately in wind tunnel calibration tests. It will generally be a higher speed than the intercept of the calibration line, because of the non-linearities at low speed. Typical threshold starting speeds (speeds below which a calm is indicated by the anemometer) are generally in the range of 0.2 to 0.4 meters per second.

Annual wind tunnel calibrations will not be needed if the torque-versus-starting-threshold is known and the sensors are not damaged. Then torque-watch tests and rotation speed tests on site are adequate and have the advantage of not removing the sensor from the tower. Removal and installation are the most frequent causes of problems with meteorological sensors.

A.5 ANEMOMETER LOCATION

The following information is taken from [17]:

> If a wind sensor is to be mounted on the top of a tower, exposure is of little concern (except with regard to terrain effects). However, if the wind sensors are to be installed on the side of a tower, care must be taken to minimize the tower influence.
>
> Some guidelines for the correct exposure of a wind sensor on an open lattice tower are as follows:
>
> 1. The boom should extend outward from a corner of the tower into the prevailing wind direction.

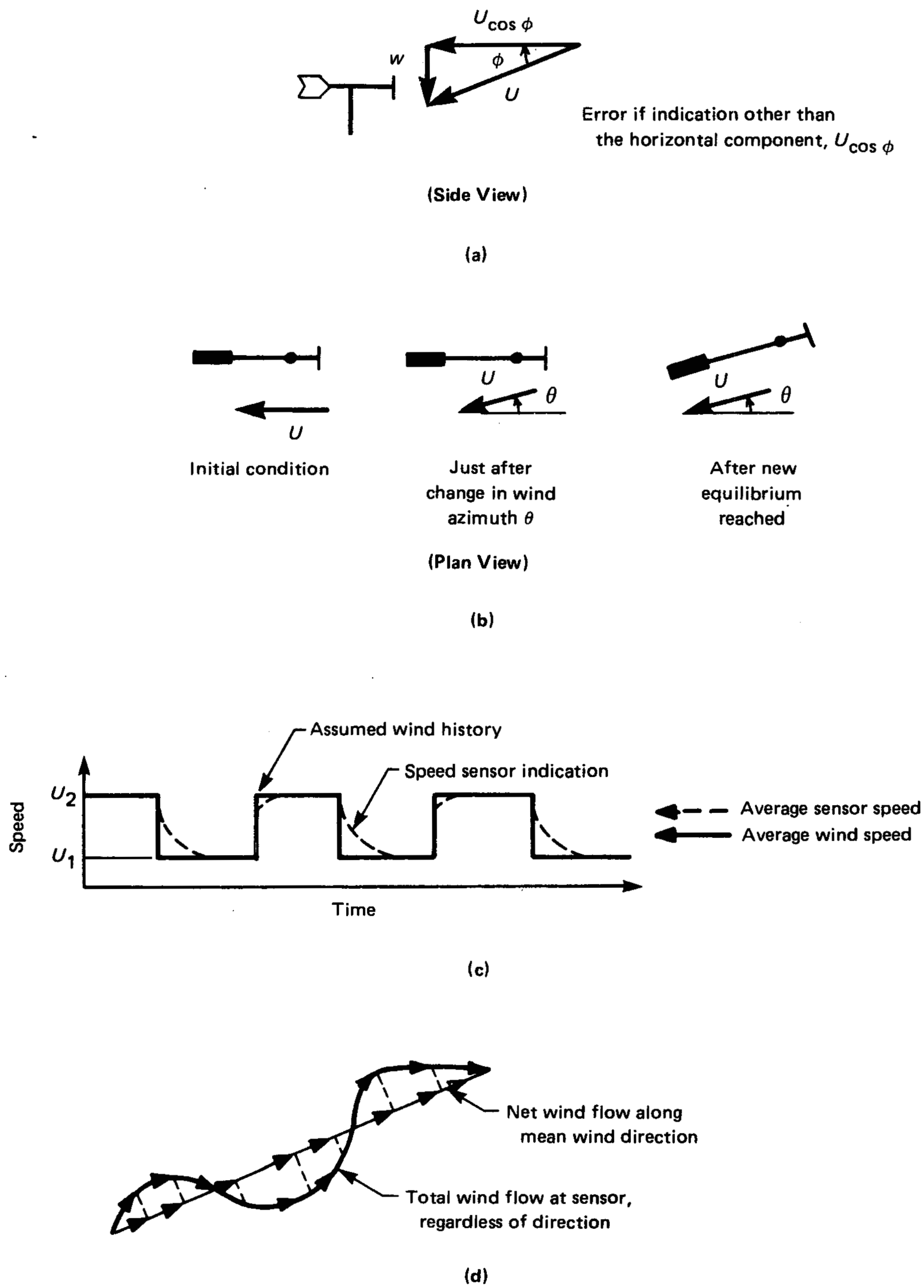


FIG. A.1 PRIMARY ANEMOMETER ERROR FACTORS: (a) W-ERROR; (b) V-ERROR; (c) U-ERROR; (d) DP-ERROR

[Adapted from MacCready (1966)]

(Reprinted by permission of the author [17])

2. The boom should extend at least three tower diameters out from the tower.

3. The wind sensors should be located in areas with minimum tower structural density, i.e., above or below horizontal cross members.

The typical vertical spacing of wind sensors for wind shear measurements should be at logarithmic elevation intervals (e.g., 10, 20, 40, 80 meters, etc.). This is because of the essentially logarithmic variation of wind speed in the atmospheric boundary layer in flat terrain.

A.6 NUMBER OF ANEMOMETERS

The issue of the recommended number of anemometers versus rotor size has been addressed in the development of this Code and in [21]. As specified in para. 4.2, duplicate anemometers at a single elevation are recommended for measurement of wind speed.

This recommendation is partially based on evaluation of two different predictions of wind energy flow through the swept area of the WT rotor, which are (1) a prediction based on a single-point measurement of wind speed, and (2) a prediction based on measuring wind speed at three elevations within the swept area. This analysis, for several wind shear conditions, is summarized as follows:

Assume an anemometer tower instrumented with three anemometers at elevations h_1, h_2, and h_3 (Fig. A.2). The wind energy calculated to be available to the rotor can be expressed by

$$E_3 = 0.5\ \varrho\ (A_1V_1^3 + A_2V_2^3 + A_3V_3^3)\ \Delta t \qquad \text{(A.5)}$$

where Δt is a time interval to convert power to energy; A_1, A_2, and A_3 are sections of the rotor swept area A; and V_1, V_2, and V_3 are the wind speeds through these sections.

For comparison, assume that the same turbine rotor is instrumented with one anemometer at elevation h_2 (Fig. A.3). The wind energy calculated to be available to the rotor would then be expressed by

$$E_1 = 0.5\ \varrho\ (AV_2^3)\Delta t \qquad \text{(A.6)}$$

in which

$$A = A_1 + A_2 + A_3 \qquad \text{(A.7)}$$

Assuming that an exponential wind speed profile exists and using the power law for wind shear effects we can write

$$V_1 = V_2\left(\frac{h_1}{h_2}\right)^{\alpha} \qquad V_3 = V_2\left(\frac{h_3}{h_2}\right)^{\alpha} \qquad \text{(A.8)}$$

where α is an empirical constant. Assume further that $A_1 = A_2 = A_3 = A/3$.

Then the wind energy calculated from these three anemometer measurements is

$$E_3 = 0.5\ \varrho\ (A/3)\ V_2^3\left[\left(\frac{h_1}{h_2}\right)^{3\alpha} + 1 + \left(\frac{h_3}{h_2}\right)^{3\alpha}\right]\Delta t \qquad \text{(A.9)}$$

We can now define E_3/E_1 as the ratio of wind energy calculated with three anemometers to the wind energy calculated with one anemometer, as follows:

$$\frac{E_3}{E_1} = \frac{1}{3}\left[\left(\frac{h_1}{h_2}\right)^{3\alpha} + 1 + \left(\frac{h_3}{h_2}\right)^{3\alpha}\right] \qquad \text{(A.10)}$$

where the elevations h_1, h_2, and h_3 are selected so that there is an area equal to $A/6$ above and below each anemometer in its section.

Table A.1 shows the calculated values of E_3/E_1 for wind turbines with "low" and "high" rotor elevations and with wind shears classified as "weak," "moderate," and "strong."

We can therefore observe that the wind energy calculated with three anemometers will be smaller than the energy value calculated with one anemometer. However, the difference is of the order of 0.5 to 1.5% and gets smaller for "high" rotor elevations. By inference, we can expect that WT predicted energies would also be very nearly the same, whether calculated from one or three anemometer measurements.

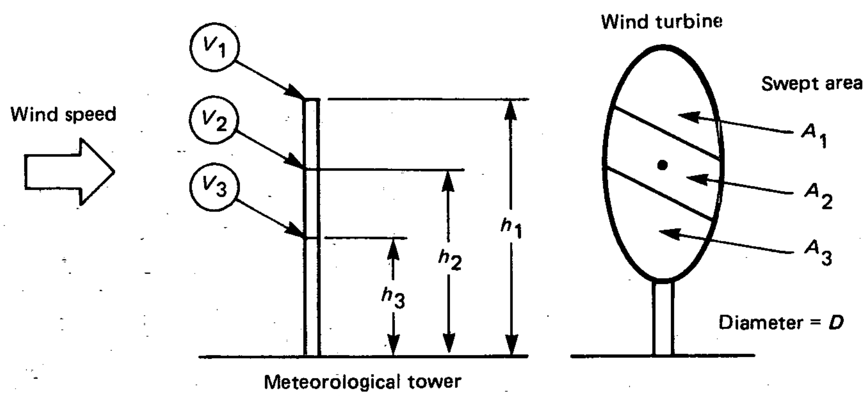


FIG. A.2 WIND SPEED MEASUREMENTS WITH THREE ANEMOMETERS

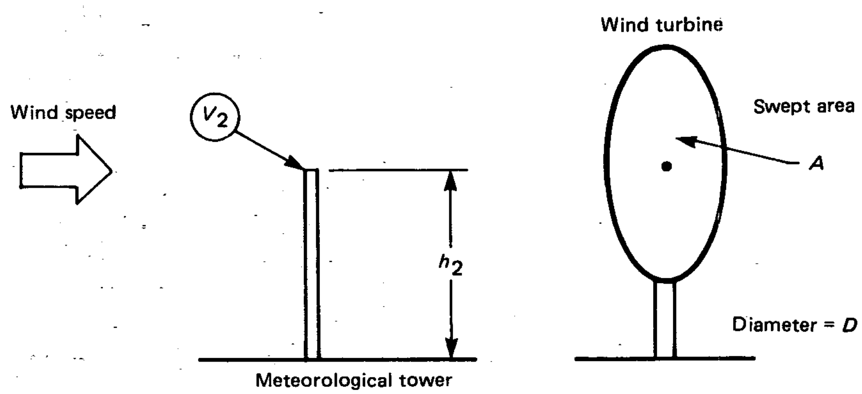


FIG. A.3 WIND SPEED MEASUREMENTS WITH ONE ANEMOMETER

TABLE A.1
EFFECT OF ROTOR ELEVATION AND WIND SHEAR STRENGTH ON WIND ENERGY RATIO E_3/E_1

Wind Shear Exponent, α	Low Rotor Elevation $h_2/D = 0.93$ $h_1/h_2 = 1.43$ $h_3/h_2 = 0.57$	High Rotor Elevation $h_2/D = 1.02$ $h_1/h_2 = 1.27$ $h_3/h_2 = 0.73$
0.10 (Weak)	0.986	0.995
0.14 (Moderate)	0.984	0.994
0.20 (Strong)	0.984	0.994

APPENDIX B
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(This Appendix is not a part of ASME/ANSI PTC 42-1988.)

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PTC 38 — Determining the Concentration of Particulate Matter in a Gas Stream 1980 (R1985)
PTC 39.1 — Condensate Removal Devices for Steam Systems 1980 (R1985)
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