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Recommended Practices for Testing Water-Pumping Windmills

Dick Veldkamp

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INDUSTRY AND ENERGY SERIES

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Dick Veldkamp

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Washington, D.C.

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and Development/THE WORLD BANK
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Washington, D.C. 20433, U.S.A.

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First printing June 1989

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Library of Congress Cataloging-in-Publication Data

Veldkamp, Dick, 1961-
Recommended practices for testing water-pumping windmills / Dick Veldkamp.
p. cm. -- (World Bank technical paper, ISSN 0253-7494 ; no. 100)
Bibliography: p.
ISBN 0-8213-1234-0
1. Wind pumps--Testing. 2. Windmills--Testing. I. Title. II. Series.
TJ926.V45 1989
627'.52--dc20 89-9107
CIP

ABSTRACT

Under the auspices of the International Bank for Reconstruction and Development (IBRD) and the United Nations Development Programme (UNDP) an international workshop on the subject of water supply by means of windpumps was held in October 1984 in Amersfoort, The Netherlands. The workshop recommended the execution of a Global Windpump Evaluation Programme (GWEP) "to generate and disseminate the information and analyses which water users, national policy makers and national and international financing agencies need to assess the technical and economic merits of wind pumping".

In November 1986 the World Bank and UNDP assigned CWD to realise an initial project for GWEP containing the following elements:

- studies on the current position and prospects for wind pumping in a variety of conditions;
- the writing of a handbook on wind pumping;
- the writing of test standards for windpumps and their implementation.

This report contains the test standards for windpump testing on test sites. (For testing and monitoring in field conditions the reader is referred to the "Handbook for Comparative Evaluation of Technical and Economic Performance of Water Pumping Systems" by CIDA, DGIS, GTZ, USAID and FAO (CWD editor).

The initial project was supported by contributions from the Government of the Netherlands, the European Community, the OPEC Fund for International Development and the UNDP Energy Account. Donor contributions were provided by cost sharing arrangements through the UNDP Energy Account. The World Bank served as the programme's executing agency and provided overall coordination and technical guidance.

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PREFACE

This document outlines standards for the testing of water pumping windmills. Such standards make it possible to compare the performance of different windmills tested at different test sites and to predict the output of a tested windmill in any wind regime.

These recommendations are based on the IEA-standards "Recommended Practices for Wind Turbine Testing and Evaluation - 1 : Power Performance Testing". In 1983 CWD developed a computer based automatic monitoring system for water pumping windmills to be applied on CWD test fields in Eindhoven, Vriezenveen and Almere (The Netherlands). This system was strongly inspired by the IEA-standards and has been used by CWD since 1984. The present recommendations incorporate four years of experience of CWD concerning the operation of its test fields.

ACKNOWLEDGEMENTS

Many useful comments and suggestions were received from:

Mr. Dave Baker
Alberta Agriculture Testfield
Lethbridge
Alberta
Canada

Mr. Hans Cleijne, Mr. Henk Oldenkamp and Mr. Paul Smulders
Wind Energy Group
Technical University Eindhoven
Faculty of Physics
Eindhoven
The Netherlands

Mr. Gareth Jones
IT Power Ltd.
Eversley
United Kingdom

Mr. Joop van Meel
Haskoning - Royal Dutch Consulting Engineers and Architects
Nijmegen
The Netherlands

Mr. K. Sunith Fernando
Wind Energy Unit
Colombo
Sri Lanka

Mr. Jorge Zapp
Centro Las Gaviotas
Bogota
Colombia

LIST OF ACRONYMS AND SYMBOLS

a	output availability [-]
A_r	area swept by rotor [m^2]
AWO	Annual Water Output [m^3]
B	barometric pressure [mbar]
B	number of bins [-]
$C_p\eta$	overall power coefficient [-]
e	quality [m^3/kg]
f_{run}	running probability [-]
f_{wind}	wind speed probability density [1/(m/s)]
g	acceleration of gravity [m/s^2]
H	pumping head [m]
i	bin number [-]
j	counter [-]
N	number of data sets or 10 minute intervals [-]
n	rotor speed [rev/s]
P	probability [-]
P_{run}	running probability [-]
P_{wind}	wind speed probability [-]
q	net water output [m^3/s]
$\bar{q}$	average water output [m^3/s]
T	air temperature [K]
V	wind speed [m/s]
$\bar{V}$	average wind speed [m/s]
$V_{anemometer}$	wind speed measured by anemometer [m/s]
V_{hub}	corrected wind speed at hub height [m/s]
V_{start}	starting wind speed [m/s]
V_{stop}	stopping wind speed [m/s]
WTP	Wind Turbine Pump
x	parameter (e.g. n, q, H, $C_p\eta$)
x_{ij}	j^{th} 10 minute average of parameter x in the i^{th} bin
$Z_{anemometer}$	anemometer height [m]
Z_{hub}	rotor hub height [m]
β	experimentally determined parameter or 1/7 [-]
ρ_T	test air density [kg/m^3]
ρ_w	water density [kg/m^3]
σ	standard deviation

INTRODUCTION: DIFFERENCES FROM ELECTRICITY GENERATING WIND TURBINES

Aspects relevant to testing in which water pumping windmills usually differ from electricity generating wind turbines are:
- the fact that water is lifted instead of electricity generated;
- the wind speed interval of operation;
- the power control and safety system;
- the presence of a large hysteresis region[1]) and the effect of the shape of the wind probability density function on the probability of operation in this area (this is the case when piston or mono pumps are used i.e. most applications of water pumping windmills).

These differences create a special problem. Generally the wind speed necessary to start the windmill from standstill is greater than the wind speed necessary to keep it running. In the interval between the stopping and starting wind speed (hysteresis region H, see fig. 1) the windmill may or may not be running depending on wind history. In a wind regime with a high average wind speed the windmill will be running more often in the hysteresis region than in a wind regime with a low average wind speed.

Because of the shape of the Overall Power Coefficient Curve for water pumping windmills (peak at low wind speed, low values at high wind speeds, Lysen [3]) a large part of the total water output may be generated precisely in this hysteresis region. Therefore the 10 minute average wind speed-water output curve is site specific: the standard IEA-procedure (Frandsen [1]) to predict output in any wind regime can not be used (Van Meel and Smulders [4], [6]).

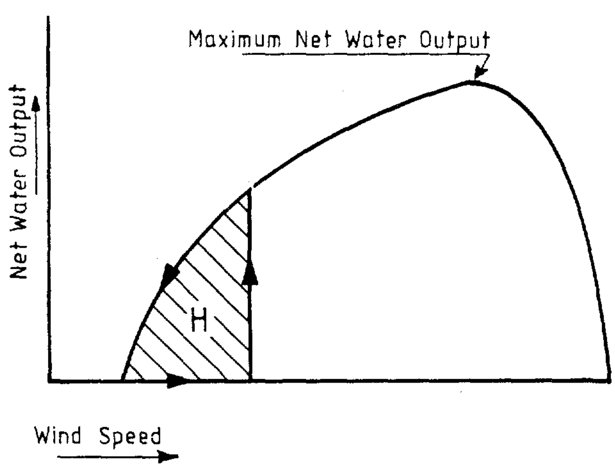

Figure 1 Hysteresis region (schematically).

A procedure to meet this difficulty is the following: the ideal water output curve is determined (the windmill is always running in the hysteresis region) which is independent of the wind regime. The water output for any wind regime is calculated by introducing a running probability function which is zero below the stopping wind speed, one above the starting wind speed and rising between these two speeds depending on the wind regime (Van Meel [5]). For any wind regime the average water output is given by:

1) *The wind speed interval between starting and stopping wind speed.*

$$\bar{q} = \int_{V_{stop}}^{V_{start}} f_{run}(V)\, f_{wind}(V)\, q(V)\, dV + \int_{V_{start}}^{V_{cut\ out}} f_{wind}(V)\, q(V)\, dV$$

where:

$\bar{q}$ = average water output [m^3/s]

f_{run} = running probability [-]

f_{wind} = wind speed probability density [1/(m/s)]

q = net water output [m^3/s]

However research is still necessary to find the procedure which establishes the ideal water output curve and the best running probability function.

For the present preliminary methods are proposed (section 6) to establish the ideal water output curve and to make output predictions for sites other than the test site.

1 DEFINITIONS AND UNITS

In this text the water pumping windmill will be called Wind Turbine Pump (WTP), machine under test or windmill.

Anemometer Distance Constant - The passage of wind in meters required for an anemometer to indicate 63% of a step function change in the input speed (WMO [8]).

Annual Water Output (AWO) - The amount of water lifted in one year.

Average Water Output ($\bar{q}$) -The Net Water Output averaged over one year.

Bin Width - The size of the Wind Speed interval used in the method of bins data analysis technique (see fig. 3).

Cut Out Wind Speed - The maximum Wind Speed at which the WTP pumps water.

Design Survival Wind Speed[2]) - The maximum speed a WTP in automatic unattended operation has been designed to sustain without damage to structural components or loss of ability to function normally.

Design Wind Speed - The Wind Speed at which the WTP operates at Maximum Overall Power Coefficient. If this speed falls within the hysteresis region the windmill is assumed to be running.

Hub Height - Height of the centre of the rotor above the terrain surface.

Hydraulic Power Output - The product of the Net Water Output and the Pumping Head.

Hysteresis Region - The wind speed interval between Stopping Wind Speed and Starting Wind Speed.

Ideal Water Output Curve - A graph which depicts the Net Water Output if the WTP were always running in the hysteresis region.

Maximum Water Output - The maximum Net Water Output in normal operation (see fig. 3).

Net Water Output (q) - The amount of water per time unit available to the user from a WTP. If nothing else is specified, q will be a 10-minute average.

Output Availability - The time fraction the windmill is pumping water.

Overall Power Coefficient ($C_p\eta$) - The ratio of Hydraulic Power Output and available Wind Power.

[2]) *In the IEA-Recommendations this is called the Maximum Design Wind Speed.*

Overall Power Coefficient Curve - A graph which depicts the Overall Power Coefficient of the entire system as a function of the Wind Speed.

Pumping Head - The total height over which the water is lifted by the windmill.

Rotor Swept Area - The area swept by the rotor.

Rotor Speed - The rotational speed of the rotor.

Rotor Speed Curve - A graph which depicts the Rotor Speed as a function of the Wind Speed.

Running - Pumping water.

Running Probability - The probability that the windmill is pumping water.

Starting Wind Speed - The Wind Speed at which the WTP starts pumping continuously in a gradually increasing wind.

Stopping Wind Speed - The Wind Speed at which the WTP stops pumping in a gradually decreasing wind.

Test Site Water Output Curve - The Water Output Curve found for the test site wind regime during the test period.

Tip Speed Ratio - The blade tip speed divided by the wind speed.

Units - Numerical values reported are to be given in metric Système Internationale (SI) units.

Water Output Curve - A graph which depicts the net water output of a WTP as a function of the Wind Speed.

Wind Power - The product of the air density divided by two, the Rotor Swept Area and the Wind Speed to the third power.

Wind Speed (V) - If nothing else is specified 10-minute average wind speed.

Wind Speed Histogram - A chart depicting the number of times the (10-minute average) Wind Speed was in a particular bin during the test period.

Wind Speed Range of Operation - Wind speeds from 0 m/s to the Cut Out Wind Speed (or 15 m/s, whichever is less).

2 THE MACHINE UNDER TEST

The WTP tested should be thoroughly described. Pertinent engineering and geometric data should be supplied. Photographs of the machine under test are desirable.

The installation procedure should be thoroughly described. In the case of a standard production model WTP installation instructions of the manufacturer should be followed.

In the case of the testing of a standard production model WTP the manufacturer should provide a clear description of the model and the serial number of the machine tested.

Listed below is a sample of important data:

Rotor: rotor size and type (horizontal/vertical axis), materials, number of blades, blade airfoil section data, hub height of the rotor. For propeller type WTP it should be stated whether the rotor is located upwind or downwind.

Safety and Control System: type and principle of operation. For yawing systems: rotor placement and eccentricity, presence, size and placement of vanes, presence and placement of springs and/or weights, angle settings of inclined hinges. For other control systems: presence of and relevant data on means of control. For all systems: possibilities of manual control.

Tower: tower type; materials; geometry.

Transmission: type; description of gear box arrangement if any; gearing ratio; stroke (if applicable), balancing weights (if applicable); schematic diagrams of unusual sub-assemblies (e.g. variable speed transmissions) if any.

Water Pump: pump size and type; geometry; presence of air chambers; stroke volume (if applicable).

Piping System: geometry of the piping system, placement of water flow measuring equipment, place of deaeration vessel, place of storage tanks if any, length and diameter of ducts, details on valves, accessories; suction and discharge head. To maintain comparability of performance of WTPs it is recommended to keep friction losses in the part of the piping system which is not prescribed by the manufacturer as small as possible.

Other information essential to the understanding of the operation of the WTP should be included.

A description of the integrated test installation should be provided. This description should include the windmill (WTP), the tower, the control systems, the transmission, the pump, the piping system and the measuring instrumentation.

3 THE TEST SITE

A description and a map of the test site should be provided. Selection of the site should be such as to minimize the possibility of local topological features affecting the test results. In situations where topological features may affect test results for certain wind directions, it is recommended that these test results be deleted or reported separately with adequate reference to possible distortions. Preferably the description of the test site should include a series of photographs taken from the place of the WTP in all directions as well as a wind compass card (wind rose).

4 FIELD TESTING METHODOLOGY

4.1 GENERAL

The basic performance characteristics of the WTP are defined by the Test Site Water Output Curve and (optionally) by the Overall Power Coefficient Curve and the Rotor Speed Curve. These curves should consist of data collected from field tests conducted under "natural" atmospheric conditions (the WTP is exposed to natural wind). Data obtained from analytical WTP model calculations, bench tests, "constant velocity" tests (towing tests) or wind tunnel tests should not be employed to generate the WTP curves.

4.2 MEASUREMENT OF ATMOSPHERIC CONDITIONS - SPECIFICATION AND LOCATION OF MONITORING INSTRUMENTS

4.2.1 Wind Speed

The anemometer employed to measure the wind speed should have a distance constant of 5 m or less. It should have an accuracy of 5% or better over the wind speed range of 4 to 15 m/s.

Calibration of the anemometer should be conducted in such a way that it can be verified that the accuracy has been maintained during the test period for the machine under test. The calibration test procedure and test results should be provided in an appendix to the WTP test report.

Use of a secondary calibration source (anemometer manufacturer, laboratory, etc.) is acceptable as long as traceability is maintained.

The guiding principle of anemometer placement should be to avoid interference effects from the WTP, the meteorological tower and the local topography.

It is strongly recommended that the test anemometer be located at hub height. At any rate the anemometer elevation should be within 10% of hub height for WTPs with a hub height of more than 10 m and within 1 meter of hub height for WTPs with a hub height of less than 10 m.

The anemometer should be placed between 2 and 6 rotor diameters from the WTP. The tower centre line should be the reference for the placement requirement on the anemometer.

For vertical axis WTP the reference diameter to be used to define the distance between the anemometer and the WTP is to be the maximum rotor diameter.

4.2.2 Wind Direction

The wind direction should be monitored in order to eliminate atmospheric data influenced by the WTP or the meteorological tower described in section 4.2.1.

The wind direction measurement should be accurate within 5 degrees. The transducer should preferably be located in the meteorological tower at the same height as the anemometer.

4.2.3 Air Temperature and Pressure

The temperature and pressure should be made in accordance with common meteorological practice.

The temperature should be measured between 1.25 and 2 m above ground level.

Air temperature and pressure at the site are measured so that the Overall Power Coefficient can be corrected to the reference air density as described in section 5.2. The accuracy in the determination of the air density should be better than 1%, and the accuracies of the temperature and pressure transducers should be good enough to meet this demand.

4.2.4 Other Environmental Parameters

Snow or rain may considerably affect both anemometer readings and water output: data obtained during such conditions should be discarded if necessary.

To quantify the effect of such conditions separate tests may be carried out, following the recommendations in all other respects.

4.3 MEASUREMENT OF PARAMETERS OF THE WTP

4.3.1 Net Water Output

The water output monitoring equipment should have an accuracy of 2% of the measured value or better for water flows between 20% and 100% of the Maximum Net Water Output.

In case of a pulsating flow (as discharged for instance by piston pumps or membrane pumps) it is strongly recommended to smoothen these pulsations e.g. by applying an overflow vessel. If pulsations are not smoothened the flow meter should be able to measure up to 300% of maximum water output.

Before flow measurement the water should be deaerated (no visible bubbles).

The water meter should be installed according to instructions of the manufacturer.

4.3.2 Pumping Head

The pumping head should be measured with an accuracy of 1% or better. Throughout the test period the pumping head should be kept within 10% of the test period average pumping head.

4.3.3 Product of Net Water Output and Pumping Head

The Net Water Output or the Pumping Head may be measured with accuracies worse than those prescribed in sections 4.3.1 and 4.3.2 if it can be demonstrated that the accuracy of their product (the Hydraulic Power Output) is 3% or better.

4.3.4 Rotor Speed (optional)

The Rotor Speed should be measured with an accuracy of 1% or better.

4.4 THE TEST PROCEDURE

4.4.1 Overview Comments

All aspects of the Test Procedure should be clearly and definitively documented so that every physical test condition could be duplicated at any later point in time. A detailed test plan should be written which addresses each applicable item in section 4 of this document as well as the additional activities necessary for the proper conduct of the test and the maintenance of the machine under test.

A number of samples consisting of wind speed, wind direction, atmospheric pressure and temperature, rotor rotational speed and water output should be taken over as wide a range of wind speeds as possible. All data should be reviewed for accuracy and consistency on a periodic basis during the test to ensure maximum reliability of the data. Appropriate test logs should be maintained to document all events during the test.

4.4.2 Elimination of Erroneous Data

If -for any reason- the measurement of wind speed, wind direction, atmospheric pressure and temperature, rotor rotational speed or water output is erroneous, the data sample should be discarded.

If during the course of the test the test anemometer is in the wake of any WTP rotor or structure the measured wind speed will deviate from the free stream wind speed. If the WTP is in the wake of any other WTP rotor or structure, the wind speed "felt" by the WTP will deviate from the free stream wind speed.

To make sure that the WTP is in the free wind stream and that the free stream wind speed is measured correctly, the following data should be discarded:

a. data where the anemometer is within a sector downstream of any WTP as defined in fig. 2;
b. data where the WTP is within a sector downstream of any other WTP as defined in fig. 2;
c. data where the anemometer is in the wake of the tower in which the instrument is mounted.

The wind direction to be used in this procedure should be the ten minute average wind direction.

Data where the 10-minute average Pumping Head is not within 10% of the test period average Pumping Head should be discarded.

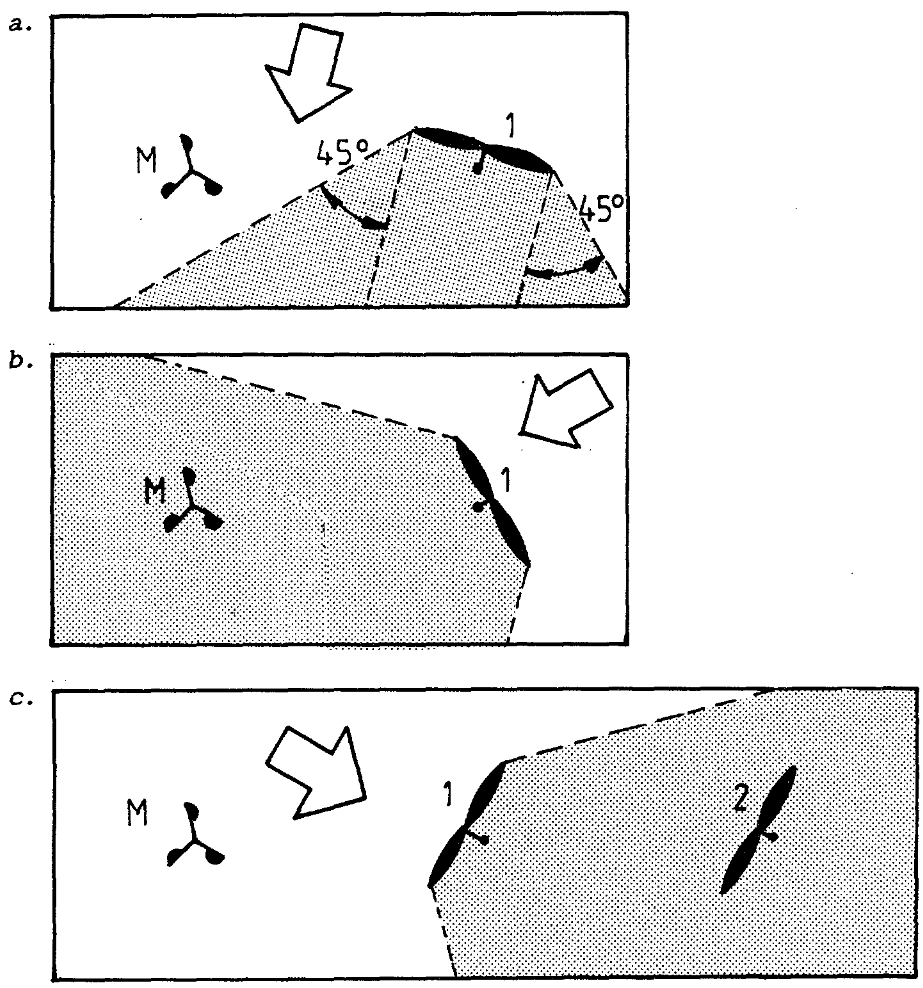

Figure 2 *Sketches showing situations in which measurements shall be discarded.*
a. Measurements of WTP1 acceptable.
b. Discard: anemometer (M) in wake of WTP1.
c. Measurements of WTP1 acceptable; discard measurements of WTP2 (in wake of WTP1).

4.4.3 Limitations on Modifications and Adjustments to the Machine under Test

Any adjustment or modification made to the machine during the test period should be reported. An engineering assessment of the impact of these changes on the WTP should be provided.

Adjustments to the load (the transmission, the pump, the piping system) should not be made in any sort of synchronization with the taking of data.

4.4.4 Maintenance and Repairs

Any maintenance or repair of the windmill required during the test period should be reported.

In the case of a standard production model WTP manufacturer recommended procedures should be followed.

4.4.5 Data acquisition

Analog Data. Data may be collected from real time recording devices, such as strip charts, analog tape recorders etc. The frequency response of the recording system should be adequate as to allow recording over the entire response frequency range of interest.

Digital Data. Automatic sampling and compiling systems are preferred under this method. Careful attention should be given to the accuracy and resolution of any analog-to-digital converters used in the data acquisition system, since they can potentially affect the outcome of the analysis procedure. The sampling frequency should be chosen so that a sufficient number of samples is available within each 10 minute period in order to obtain the prescribed accuracies.

It is recommended to use integrating measuring devices e.g. pulse counters.

4.4.6 Data Base Requirements

The total data base is formed by a number of test periods of limited duration. If the duration of such a test period is less than 15 minutes that test should be considered invalid and the associated data should be discarded.

Before analysis of the data begins, erroneous samples (section 4.4.2) should be discarded and the remaining samples reduced to sets of ten minute average values. Each of these 10 minute average values should be calculated from an uninterrupted row of samples, i.e. none of the samples should be missing due to malfunctioning of the instruments or due to wake-conditions.

The testing should not be considered complete until the following conditions for the reduced data have been met:

- A total of 3000 sets of 10 minute average values of recorded operation of the WTP must have been obtained before the determination of the water output curve;
- The minimum number of sets of 10-minute average values per bin is 10 (see section 5.3).

5 ANALYSIS OF FIELD TEST RESULTS

5.1 WIND SHEAR CORRECTION

If the test anemometer is not at hub height, all wind speed data are to be corrected for wind shear effect.

The preferred method is to multiply the measured wind speeds by a correction factor that has been experimentally determined at the test site. This factor represents the long term average ratio of wind speeds at anemometer and hub height. A power law may be used in which the ratio of heights is raised to the power β and used as the correction factor:

$$V_{hub} = \left[\frac{Z_{hub}}{Z_{anemometer}} \right]^{\beta} V_{anemometer}$$

where:

V_{hub} = corrected wind speed at hub height [m/s]

Z_{hub} = rotor hub height [m]

$Z_{anemometer}$ = anemometer height [m]

β = experimentally determined exponent or 1/7

$V_{anemometer}$ = wind speed measured by anemometer [m/s]

The method of correction chosen shall be reported.

5.2 CALCULATION OF AIR DENSITY

The test air density is calculated for each 10-minute average test period by applying the following formula:

$$\rho_T = 1.225 \left[\frac{288.15}{T} \right] \left[\frac{B}{1013.3} \right]$$

where:

ρ_T = test air density [kg/m^3]

T = air temperature [K]

B = barometric pressure [mbar]

5.3 DETERMINATION OF CURVES FROM DATA

The curves which describe the WTP performance are the Net Water Output Curve, the Rotor Speed Curve and the Overall Power Coefficient Curve. The last two curves are optional; however here it is assumed that all curves will be determined. To be able to better judge the results a wind speed histogram should be added.

After the reduction and correction of the data, data analysis is to be performed using the method of bins (Trenka [7]). In this procedure the Wind Speed Range of Operation is divided into separate intervals (bins). The wind speed bin width is 0.5 m/s. Each bin has four cumulative registers:
-one for wind speed;
-one for rotor rotational speed;
-one for net water output;
-one for pumping head.

A data set consists of the 10 minute average of the Wind Speed, the Rotor Speed (optional), the Net Water Output and the Pumping Head. Data sets should be accumulated in bins, the Wind Speed determining the specific bin. Then the ensemble average of the data sets in each bin should be determined by dividing the summed value of the wind speed data sets by the number of data sets, and by dividing the Rotor Speed, the Net Water Output and the Pumping Head by the number of data sets i.e.:

$$V_i = \frac{1}{N_i}\sum_{j=1}^{n} V_{ij}$$

$$n_i = \frac{1}{N_i}\sum_{j=1}^{n} n_{ij}$$

$$q_i = \frac{1}{N_i}\sum_{j=1}^{n} q_{ij}$$

$$H_i = \frac{1}{N_i}\sum_{j=1}^{n} H_{ij}$$

where:

N_i = number of data sets in the i^{th} bin
V_{ij} = j^{th} 10 minute average of wind speed in the i^{th} bin
n_{ij} = j^{th} 10 minute average of rotor speed in the i^{th} bin
q_{ij} = j^{th} 10 minute average of water output in the i^{th} bin
H_{ij} = j^{th} 10 minute average of pumping head in the i^{th} bin

The ensemble averages (V_i, q_i) and (V_i, n_i) are then plotted and curves fitted through the plotted points. The fitted curves are the Site Net Water Output Curve, and the Site Rotor Speed Curve.

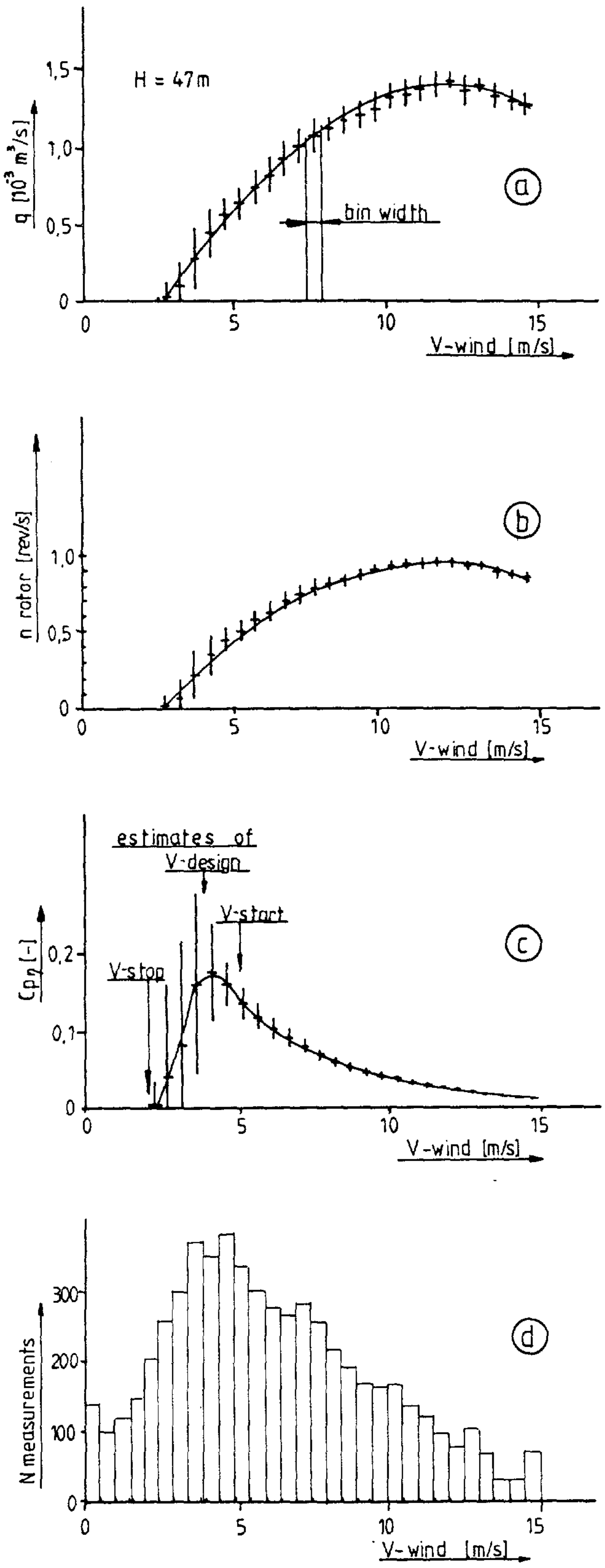

Figure 3   *a. Water Output Curve*
b. Rotor Speed Curve
c. Overall Power Coefficient Curve
d. Wind Speed Histogram

Furthermore the Overall Power Coefficient Curve is derived from the data by using:

$$C_P\eta_i = \frac{\rho_w \, g \, H_i \, q_i}{\rho_T/2 \; A_r \; V_i^3}$$

where:

$C_P\eta_i$ = overall power coefficient in the i^{th} bin [-]
ρ_w = water density [kg/m^3]
g = acceleration of gravity [m/s^2]
ρ_T = test air density [kg/m^3]
A_r = area swept by the rotor [m^2]
V_i = average wind speed in the i^{th} bin [m/s]

The curves should be established only after the minimum conditions of section 4.4.2 and 4.4.5 have been met.

The curves are linearly scaled Cartesian coordinate system graphs. See fig. 3.

Both scales start at zero. The ordinate scale should extend to at least 110% of the maximum value of the Net Water Output, the Rotor Speed and the Overall Power Coefficient.

The curves should be displayed graphically as indicated in fig. 3 and in the form of a table as shown in fig. 4.

In the graph of the Net Water Output the Pumping Head is to be given.

It is recommended that the standard deviation of the Rotor Speed, Water Output, Overall Power Coefficient and Pumping Head be given in the table (fig. 4) and depicted by vertical line segments in the graph (fig. 3).

The standard deviation of a parameter x in the i^{th} bin is given by:

$$\sigma_{x,i} = \sqrt{\frac{\sum_{j=1}^{N_i} \left[x_{ij} - \sum_{j=1}^{N_i} \frac{x_{ij}}{N_i} \right]^2}{N_i - 1}}$$

where:

$\sigma_{x,i}$ = standard deviation of x-values in the i^{th} bin

x_{ij} = j^{th} 10 minute average of parameter x in the i^{th} bin (x is e.g. n_i, q_i, H_i, $C_P\eta_i$)

N_i = number of data sets in the i^{th} bin

				bin sample averages							
bin	bin intervals	number of reduced data sets	wind speed	rotor rotational speed		water flow		overall power coefficient		pumping head	
	[m/s]		[m/s]	[rev/s]		[ltr/s]		[%]		[m]	
			V_i	n_i	σ_{n_i}	q_i	σ_{q_i}	$C_P\eta$	$\sigma_{C_P\eta_i}$	H_i	σ_{H_i}
1	0.0-0.5	99	0.36	<0.01	<0.01	<0.01	<0.01	0.0	0.0	47.1	0.0
2	0.5-1.0	84	0.77	<0.01	<0.01	<0.01	<0.01	0.0	0.0	47.1	0.0
3	1.0-1.5	127	1.28	<0.01	<0.01	<0.01	<0.01	0.0	0.0	47.1	0.0
.	...	.	.	.	.	.	.	.	.	.	.
.	...	.	.	.	.	.	.	.	.	.	.
10	4.5-5.0	555	4.77	0.44	0.07	0.56	0.10	15.9	2.8	47.0	0.1
11	5.0-5.5	606	5.25	0.50	0.06	0.63	0.10	13.5	2.2	47.0	0.1
.	...	.	.	.	.	.	.	.	.	.	.
.	...	.	.	.	.	.	.	.	.	.	.

Figure 4. Example of table containing the results of the method of bin analysis.

6 DERIVED RESULTS

6.1 ANNUAL WATER OUTPUT

The Test Site Annual Water Output should be calculated. It is defined as:

$$AWO = 365 \cdot 24 \cdot 3600\ \bar{q}$$

where:

$$\bar{q} = \int_{0}^{V_{cut\ out}} f_{wind}(V)\ q(V)\ dV$$

and where:

$f_{wind}(V)$ = wind speed probability density function at the test site during the testing period [1/(m/s)]

$q(V)$ = experimentally determined Net Water Output [m^3/s]

The integral given here may be calculated by:

$$\bar{q} = \sum_{i=1}^{B} P_{wind,i}\ q_i$$

where:

B = number of bins

$P_{wind,i}$ = wind speed probability for the i^{th} bin

q_i = average water flow rate for the i^{th} bin

6.2 QUALITY FACTOR

The WTP Quality Factor should be calculated. This parameter, which is an efficiency number, is independent of the size of the WTP, the discharge head and the pump. It is given by (Lysen [3]):

$$e = \frac{\rho_w\ g\ H_{total}\ \bar{q}}{A_r\ \bar{V}^3}$$

where:

e = quality [m^3/kg]

ρ_w = water density [kg/m^3]

g = acceleration of gravity [m/s^2]

H_{total} = total pumping head [m]

$\bar{q}$ = average water flow rate over the test period [m^3/s]

A_r = area swept by the rotor [m^2]

$\bar{V}$ = average wind speed over the test period [m/s]

With the quality factor the average air density during the test period should be reported.

6.3 OUTPUT AVAILABILITY

The Test Site Output Availability (the time fraction the windmill is pumping water) is expressed by:

$$a = \frac{N_{running}}{N_{total}}$$

where:

a = output availability [-]

$N_{running}$ = number of 10 minute intervals in which the WTP was pumping water [-]

N_{total} = total number of 10 minute intervals during which measurements were performed [-]

6.4 STARTING AND STOPPING WIND SPEEDS

The starting and stopping wind speed should be estimated from the test results. The standard deviations of the Rotor Speed, Net Water Output and Overall Power Coefficient (fig. 3) can be used to estimate the width of the hysteresis region.

It is recommended that some measurements of the starting wind speed be performed by visual observation of the rotor behaviour in gradually rising and gradually falling wind conditions.

The exact procedure followed should always be described.

With the figures for the starting and stopping wind speed the air density should be reported.

6.5 IDEAL NET WATER OUTPUT CURVE *(provisional)*

To make the output of windmills comparable it is necessary to know the Ideal Net Water Output Curve and the Starting and Stopping Wind Speeds. The Ideal Net Water Output Curve is the curve that would be found if the windmill were always pumping water in the hysteresis region. If this curve is known, output predictions for this windmill-pump combination may be made for any wind regime.

So far no thoroughly tested method for this inference has been presented. Rather than creating a false sense of reliability by presenting methods in detail, a general discussion of the issue is provided here together with some literature references.

Those who are testing WTPs and determining the Ideal Net Water Output Curve are invited to document their methods and findings in a detailed manner for possible input as data in future research activities.

6.5.1 Systems without hysteresis

For systems without hysteresis (starting wind speed equals stopping wind speed) the Ideal Net Water Output Curve equals the Test Site Net Water Output Curve:

$$q_{ideal} = q_{measured}$$

When applying this method evidence should be presented to show that it is reasonable to regard the WTP as having no hysteresis.

6.5.2 Systems with hysteresis - direct methods

A Plotting all 10 minute average values

It is possible to determine the Ideal Net Water Output Curve by plotting all 10 minute averages as separate points instead of determining the bin averages; the Ideal Net Water Output Curve is given by the upper boundary of the cloud of points (fig. 5 next page, Kenna [2]).

B Selecting data

It is possible to determine the Ideal Net Water Output Curve by measuring the relevant parameters every second and calculating the averages over a short time period (e.g. 5 seconds): this period must be short to prevent the WTP from stopping and starting again within the averaging time interval. From all averages determined in this way those points lying on the Ideal Net Water Output Curve (the upper boundary of the hysteresis region) must be selected.

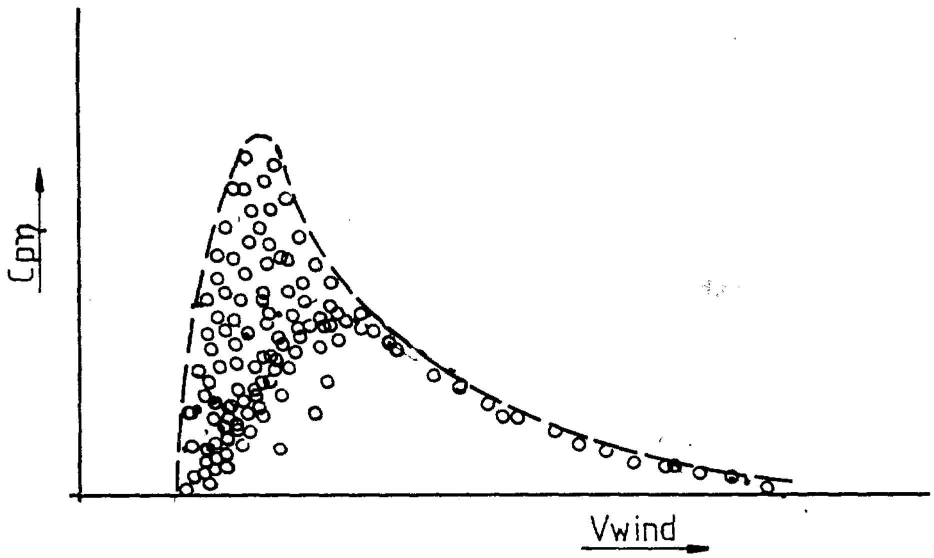

Figure 5 Plot of all 10-minute averages

Criteria for selection of a data set (one time interval) may be:

- a wind speed restriction. To ensure steady operation in this particular data set the wind speed must have been constant before for a certain period (e.g. 1 measuring interval). "Constant" may be expressed in terms of minimum and maximum wind speeds or standard deviation.

- a restriction on tip speed ratio. If no selection is made extremely high Overall Power Coefficients will be found in those measuring intervals where the wind was falling: the rotor is turning faster and water output is higher than in accordance with steady operation at this wind speed. Hence a selection criterion may be that the tip speed ratio must never be greater than the maximum tip speed ratio (which may be determined by making the windmill run unloaded with the rotor perpendicular to the wind).

  On the other hand the tip speed ratio must always be greater than the tip speed ratio with maximum torque coefficient on the Ideal Net Water Output Curve. A safe boundary for this tip speed ratio is the design tip speed ratio, which may be estimated to be 4/7 of the maximum tip speed ratio (Van Meel [6]).

To judge whether a good selection has been made the standard deviation of the selected values may be used: in the hysteresis region this number should be considerably smaller than the standard deviation of the 10-minute average curve.

C Selection of measuring period on wind regime

Another method of finding the Ideal Water Output Curve is following the normal IEA 10-minute procedure but to select time periods in which strong winds prevail (Van Meel [5,6]). The probability that the windmill is running will be greater if the wind speed is predominantly above the starting wind speed; hence the averaged curve will approach the Ideal Curve.

6.5.3 Systems with hysteresis - indirect method

Apart from the direct approach to determining the Ideal Net Water Output Curve, an indirect approach may be followed. Theoretically it is possible to construct the Ideal net Water Output Curve from the measured curve if the nature of the wind regime during the test period is known. Between the starting and the stopping wind speed we have:

$$f_{run}(V)\ q_{ideal}(V) = q_{measured}(V) \qquad V_{stop} < V < V_{start}$$

This implies that is possible to derive the ideal curve from the measured curve if the running probability function is known.

By considering the wind speed history it can be shown that the total probability that the windmill is running in the hysteresis may be estimated by (Van Meel [5]):

$$P_{run} = \frac{P(\ V > V_{start}\ )}{P(\ V < V_{stop}\ ) + P(\ V > V_{start}\ )}$$

Any running probability function must be consistent with this total probability. Furthermore it must be zero at the stopping wind speed.

It must be noted that the success of this approach is highly dependent on the correctness of the values of starting and stopping wind speeds: these values have great influence on the probability function.

Furthermore a problem may be encountered in determining the Ideal Water Output Curve at wind speeds close to the Stopping Wind Speed. The measured water output is divided by the running probability which would be very small.

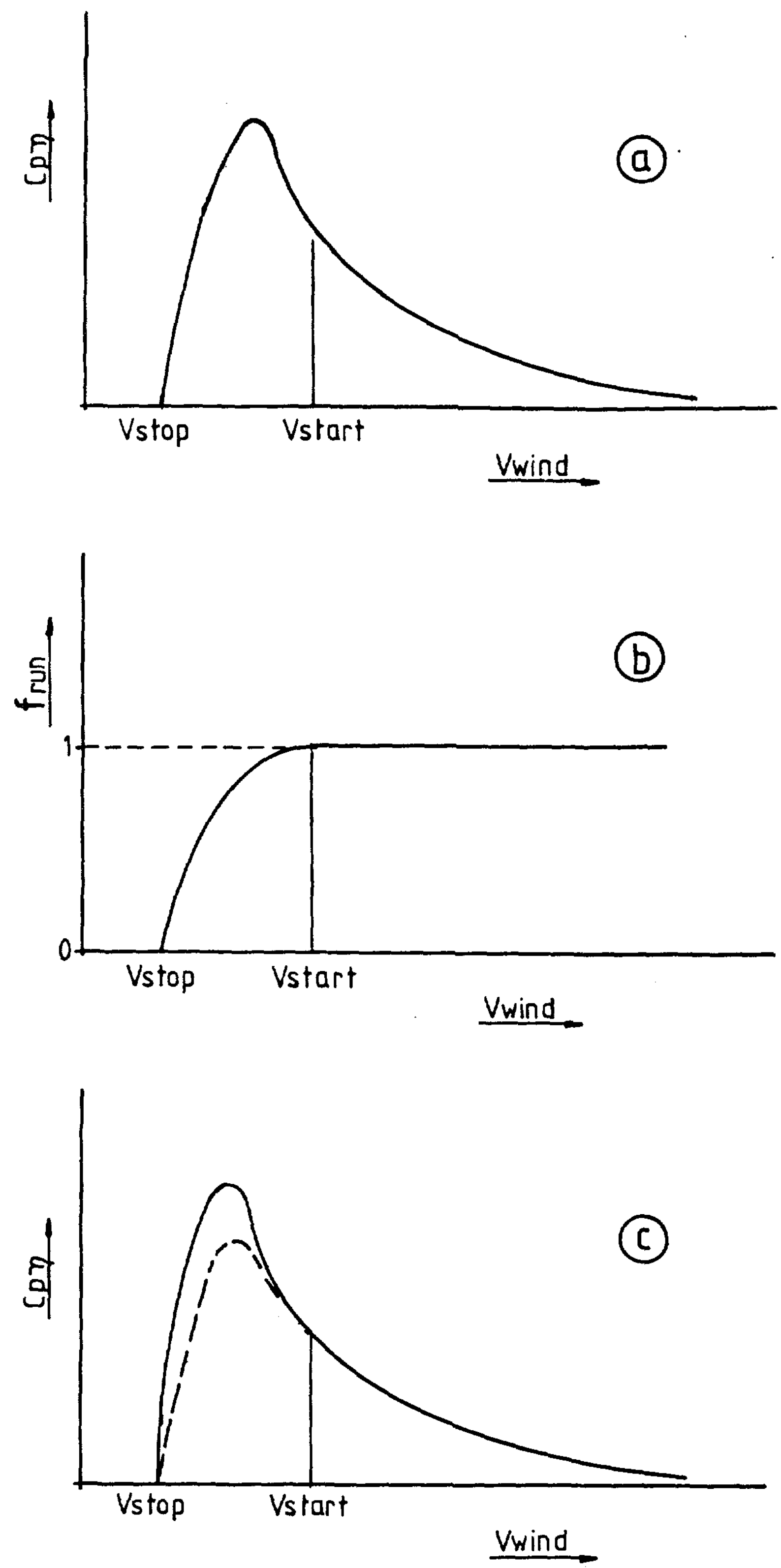

Figure 6 *Construction of Ideal Water Output Curve from Measured Water Output Curve.*

a. Measured Water Output Curve
b. Running Probability Function
c. Ideal Water Output Curve

6.5.4 Starting and stopping wind speeds

By comparing the Ideal Net Water Output Curve (found with method A, B or C, see section 6.5.2) and the 10 minute average curve, starting and stopping wind speeds may be found: the Starting Wind Speed is the wind speed where both curves join (see fig. 7). However this method may present difficulties: especially in wind regimes with high average wind speeds the 10 minute average curve is bound to follow the ideal curve closely at the right side of the hysteresis region (Van Meel and Smulders [5]).

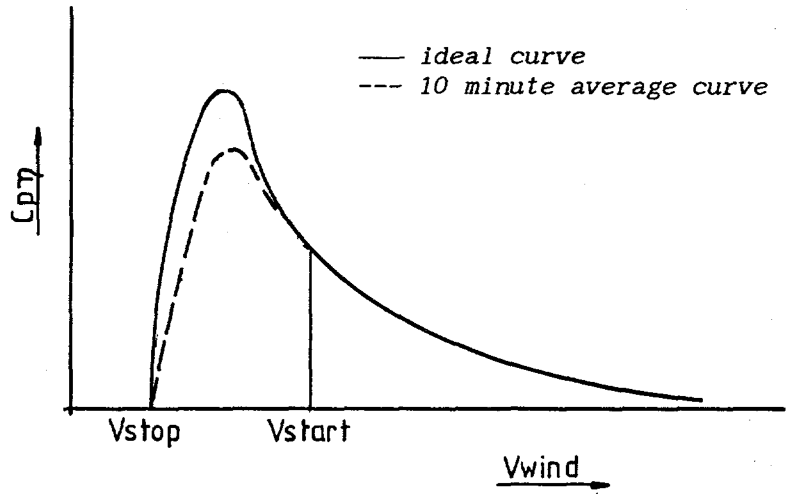

Figure 7 Finding starting and stopping wind speeds by comparing Ideal Net Water Output Curve and 10 minute average curve.

7 TEST REPORT FORMAT

In summary, the Test Report should include, but not be limited to, the items listed below.

1. Machine under Test, including model and serial number if a production machine.
2. Instrumentation including type and location. If calibration is applicable, the method of calibration used, the calibration time interval used and the traceability of the calibration references to National Standards.
3. Site lay out (including sketch and photographs).
4. Data acquisition system.
5. Installation procedures followed.
6. Load (Transmission, Pump and Piping System).
7. Weather data.
8. Data corrections used.
9. Deviations from recommended practice.

Raw data summaries should be included as an appendix to the report.

Plots of the following should be presented:

10. Wind Speed Probability versus Wind Speed (Wind Speed Histogram)
11. Net Water Output versus Wind Speed.
12. Rotor Speed versus Wind Speed.
13. Overall Power Coefficient versus Wind Speed.

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Cover Design by Bill Fraser

ISSN 0253-7494
ISBN 0-8213-1234-0

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