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Projektleitung Energieforschung
International Energy Agency IEA

Implementing Agreement for Co-Operation in the Development of Large Scale Wind Energy Conversion Systems

Third Meeting of Experts - Data Acquisition and Analysis for Large Scale Wind Energy Conversion Systems

Organised by
Project Management for Energy Research (PLE) of the
Nuclear Research Establishment Jülich (KFA)
on behalf of the
Federal Minister of Research and Technology
in cooperation with DOE, Washington D.C.

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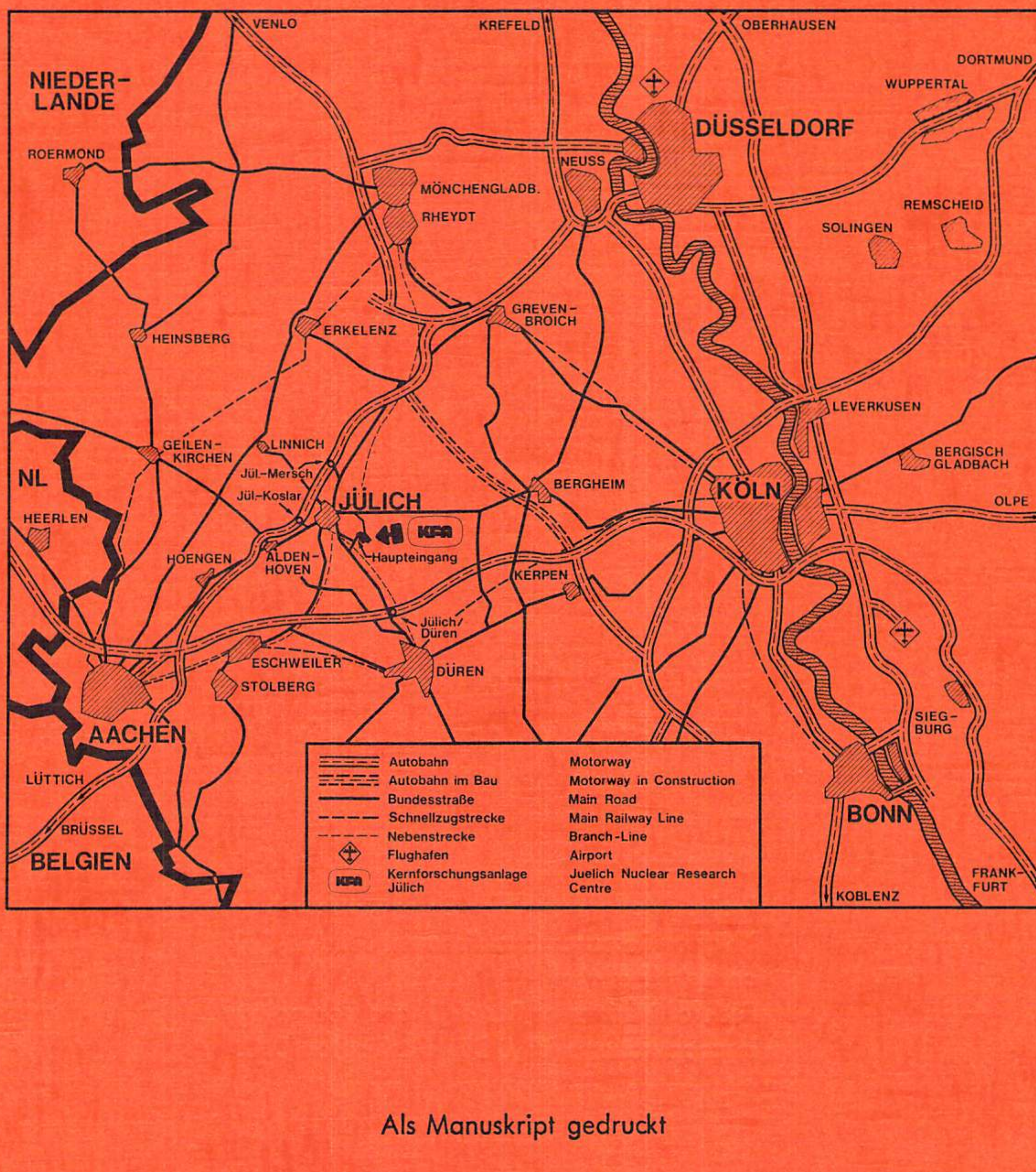

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Blowing Rock, North Carolina, Sept. 26-27, 1979

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Project Management for Energy Research (PLE) of the
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Scientific Coordination:
R. Meggle (MBB München) and R. Windheim (PLE KFA)

C O N T E N T S

The two following contributions to the expert meeting
are not copied:

E. KADLEC (Sandia Laboratory, Albuquerque, USA)
Testing and Evaluation of Darrieus vertical
Axis Wind Turbines

A. S. SMEDMAN (Uppsala University, Sweden)
Measurements of Wind Speed in Relation to procuded
Power at a Wind Turbine Site

The programme includes an afternoon-tour to the DOE/Nasa
2000 kW MOD-1 Wind Energy Converter at Howard's Knob near Boone.

DOE/NASA 2000kW EXPERIMENTAL WIND TURBINE

Howard's Knob, Boone, North Carolina

2000 KILOWATT WIND TURBINE SPECIFICATION

Rotor

Number of blades	2
Diameter, ft	200
Speed, rpm	35
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable Pitch
Cone angle, deg	9
Tilt angle, deg	0

Blade

Length, ft	97
Material	Steel Spar/Foam Trailing Edge
Weight, lb/blade	21,500
Airfoil	NACA 44XX
Twist, deg	11
Tip chord, ft	2.8
Root chord, ft	12
Chord taper	Linear

Tower

Type	Pipe truss
Height, ft	131
Ground clearance, ft	40
Hub height, ft	140
Access	Hoist

Transmission

Type	Three-stage conventional
Ratio	51
Rating, hp	2209

Generator

Type	Synchronous ac
Rating, kVA	2225
Power factor	0.8
Voltage, V	4160 (three phase)
Speed, rpm	1800
Frequency, Hz	60

Orientation drive

Type	Ring gear
Yaw rate, degree/sec	.25
Yaw drive	Hydraulic

Control system

Supervisory	Computer
Pitch actuator	Hydraulic

Performance

Rated power, kW	2 000
Wind speed at 30 ft, mph:	
Cut-in	11
Rated	25.5
Cut-out	35
Maximum design	125

Weight klb)

Rotor (including blades)	103
Above tower	330
Tower	320
To'al	650

The Measurement System used at the Gedser Windmill Purpose, Performance and Experience.

Per Lundsager, Risø National Laboratory,
DK 4000 Roskilde, Denmark.

Abstract

The paper summarizes the experiences gathered with the measurement system used in a series of measurements made on the Gedser windmill during the period Oct. 1977 - Apr. 1979. The layout of the system and the measurement procedures used are motivated and described, and the performance of the system is evaluated.

Presented at: IEA-Implementing Agreement LS-WECS:
3rd Expert Meeting Sept. 25-27, 1979,
Boone, North Carolina, USA.

1. Introduction

In the period Oct 1977 to April 1979 a series of measurements on the Gedser Wind mill was carried out as reported in refs. 1 to 6. The measurement program was carried out under contract with the Research Association of the Danish Electricity Supply Undertakings (DEFU) in cooperation with US Energy Research and Development Administration (US ERDA) as a joint venture by Risø National Laboratory, Structural Research Laboratory of the Technical University of Denmark (SRL) and Danish Ship Research Laboratory (DSRL).

The field measurements are terminated and the data processing is well under way, and therefore time has come for an evaluation of the results of the efforts put into the project. The purpose of this presentation is to evaluate the measurement system in a broad sense, i.e. not only the measurement system itself, but also the way it was used. Fig. 1.1 shows the main points in the presentation, which concludes with a series of recommendations of both what to do and what not to do, based on the experiences at the Gedser Windmill.

2. The Measurement Program

The figures 2.1 and 2.2 show the object of the measurements, which is the last and largest of 3 research windmills built in the 1950's by SEAS (Southeast Zealand Electricity Ltd.) and DEF (The Danish Association of Electricity Supply Undertakings). Fig. 2.3 shows a summary of the characteristics of the mill, which deviates from the majority of new designs in that the rotor is 3 bladed, upwind located and stall regulated. The blades are stiffened by a number of stays.

Very few of the large windmills hitherto built have avoided major problems. One of those who did succeed is the Gedser windmill which was in continuous automatic operation during the years 1958-67 without major mechanical troubles, and thus the design of the Gedser mill has proven to be quite successful for its time. It is therefore of considerable interest to verify the design by studying the structural and aerodynamic response as well as the power production as a function of meteorological conditions.

The main objectives for the measuring program was, cf. fig. 2.4, the determination of power carves, loads and response, and power fluctuations. However, the lay-out of the instrumentation also aimed at obtaining results that may be useful in the evaluation and development of models for windmill design and analysis. Furthermore the results may be of interest in a comparison with later designs of USA and Sweden, which have several essentially different design features.

In order to meet these requirements, the measurement program outlined in fig. 2.5 was carried through. When studying the structural response one must be able to resolve frequencies up to several Hz. On the other hand one is interested in the long time performance as far as power production goes. In order to limit the amount of data needed the division in short term and long term measurements was considered necessary, and the program therefore consisted of a long term part and a short term part. The long term part contained continuously recording of wind and electric power data in order to describe the site climatology and to establish an average power curve. The short term part consisted of a number of runs of approximately 1 hours duration, during which measurements of wind, power and structural response were made together with the recording of various operational parameters, using a high scanning rate. A limited number of rotor channels were available, and it was decided to instrument two of the three blades rather extensively in order to get the best possible description of the blade behaviour. The third blade was not instrumented.

3. The Measurement System

The measurement system consisted of sensors of various types, data transmission systems and data recorders.

The sensor types are outlined in fig. 3.1, where they are grouped according to the type of information given by them. Most of the sensor types were off-the-shelf items, exceptions being the position indicators and some of the strain gauges. Most of the strain gauges were exposed to the environment, being mounted externally on the structure. They were mounted using the cement and moisture protection specified in fig. 3.1.

The data transmission of the short term measurements is shown scematically in fig. 3.2. High speed samplings of the signals are recorded on magnetic tape by means of three recording systems: 1) An integrated digitizer/raidolink/digital/magnetic tape recorder-system 2) a 60-channel digitizer digital/magnetic tape recorder built into a recording van and 3) a microcomputer using paper print-out. Fig. 3.3 shows the main characteristics of the digital telemetry system and the recording van. Fig. 3.4 shows the data flow during long term measurements.

The main problem in setting up the experiment was the data transmission from the rotor to the ground. Therefore it was decided to include two different transmission systems 1) the digital transmission system mentioned above and 2) an analog transmission system. None of the two systems had been used before in a similar application.

The use of two independent wireless telemetry systems was a consequence of the fact, that the limited time available made it necessary to use already existing telemetry systems. However, both telemetry systems had troubles at the mill as will be described later, the analog system being still under development and the digital system being a prototype developed for stationary long distance telemetry.

The digital telemetry system transmits and records signals from 26 sensors on blade 3. A box containing 28 operational amplifiers (Make CIL type SGA706) was built for the purpose. This amplifier box supplied the feed voltage (3 volts) for the strain gauge bridges on the blade and amplified the signals by 2000 x. The strain gauge bridge will give $\sim$ 7μV/ strain and is amplified to 14 mV/μstrain. The signals are fed into the digitizer/transmitter part of the telemetry system. A multiplexer samples 28 signals, 2 synchronizing signals and two scan counter bytes in a regular pattern at a frequency of 1600 Hz, which means 50 Hz for each instrument. The signals are digitized into a series of 8 bits, which is encoded onto a 2256 Mhz radio transmitter (s-band, frequency modulated). Upon receipt of the bit stream by the ground based receiver, the signals are decoded into 8 bit bytes again, using the synchronizing words to identify the complete scan, and consequently recorded on computer compatible magnetic tape consists of 64 scans, each of 32 8-bit bytes representing a scan of 32 instruments, i.e. 2048 bytes. Thus the measurement results are represented by an integer number between 0 and 255 on the tape. A change of this number by 1 represents a voltage change on the input to the digitizer by 8 mV or ∿ ½μstrain. Two points of interest for the data user should be emphasized:

1) The sampling is serial, i.e. the numbers in one scan are sampled at equidistant moments, 0.6 msec apart.

2) The system measures instantaneous values, not averages. On the other hand an RC-filter of 100 Hz is used on each sensor, providing for some anti-aliasing.

The analog telemetry system was meant as an extra back-up system to secure that data from the rotor were obtained in case of data transmission problems. The system is an analog multiplexer sampling 16 signals at 250 Hz/channel. The channels are read out and kept in parallel for each scan and after turn gated to the A/F converter for FM transmission. Scan length and speed are controlled from "ground station" by telemetry. At the "ground stage" F/V conversion, demultiplexing and samplehold take place before readout in 16 parallel channels. Unfortunately this system suffered heavily from noise problems, mainly stemming from weaknesses in the FM transmission system.

The recording van samples the signals from the ground based sensors. The system can record 60 channels simultaneously with individual sampling rates. Each input channel is basically a pulse counter that counts over the chosen sampling period. Each channel is furthermore equipped with an analogue-to-pulse rate converter that adapts analogue signals to the pulse input. In this fashion each channel can accept analogue or pulse rate input as chosen individually. The number of counts during a sampling period is recorded on computer compatible tape together with a channel number. Each instrument reading consists of 1 8-bit bytes for the channel number and 2 8-bit bytes for the result (12 bits resolution only). The magnetic tape unit is 9-track, 800 bpi and uses 1800 ft tapes. Each block on the tape contains 682 3 byte readings or 2046 8 bit bytes.

As the input channels are pulse counters, the results are blockaveraged over the sampling period in contrast to the digital telemetry system. However, a few of the sensors provided the recording systems with too few pulses per 20 msec to produce a proper resolution of the signals. These channels were modified to measure the time lag between the pulses. A 100 kHz pulse generator, which is triggered by the arrival of a sensor pulse and stopped upon the arrival of the next one, is connected into a pulse-counting input. Scans that contain a count rate intermediate between 0 and 200 p/20 ms make the arrival of a sensor pulse. The exact count rate of such an "unfilled" scan yields a precise time in units of 10^{-5} sec.

The recording van and telemetry system was synchronized together: the telemetry system scan-counter triggered the bus sampling. The scan number from the telemetry system was recorded on the van tape too so that simultaneous scans from the two tapes can be easily extracted.

The microprocessor

The microprocessor is used to give immediate reading of wind-speed and -direction and power during runs or otherwise. The parameters are sampled at 4 Hz and on-line calculation of average wind speed and mean power are made over a chosen period of time. The output is immediately printed on paper.

The frequency range that can be covered in the short term measurements is limited by the wish to limit the data files to reasonable sizes. With the instrumentation at hand a full 9-track 800 bpi, 1800 ft tape can store 100.000 scans or ∿ 5 decades in the spectrum. We have chosen to use runs of appr. 40 min. each with a scanning rate of 50 Hz (100.000 scans). This gives a high frequency cut-off of 25 Hz, which seems reasonable in comparison with the expected dynamic resonance frequencies

(0.01 Hz - ~ 5 Hz) as it allows the possible study of one or two higher harmonics also. 40 min. is more than enough to cover the slow resonances (turning of the nacelle). From a meteorological point of view 40 min. cover the whole turbulent part of the spectra (10 min. averages are common meteorology practice) and hits close to the spectral gap between turbulence and synoptic region in the wind spectrum.

The result of each run during the short sessions on the Gedser windmill is two digital magnetic tapes. Although the sampling on the two main systems are synchronized, the block length and structure are different and the data handling software is different.

To facilitate the data access, the contents of the two tapes are transferred to a disc pack and erroneous scans are exchanged with the latest correct one. The two sets of data files are now merged together to form the final data set. It should be noted, that originally recorded datavalues (in 8- and 12 bit integer words) have been conserved through the conversion process to save space on the disc pack. Each data value is now stored in C2-format (16 bit). The structure of the data files has been fixed to be the same for all runs.

The data quality is tested by making various plots and by computing averages for the whole run for all sensors. Once the data have been tested, they are dumped on magnetic, unlabeled tapes (multi-reels). The values still being raw data, they have to be converted when read. The data processing is summarized in fig. 3.5.

4. Measurement procedures

Fig. 4.1 shows the mounting of rotorinstrumentation and gives an idea of the rather difficult access to the externally mounted equipment, which was through a manhole on top of the nacelle.

Fig. 4.2 summarizes the problems encountered during mounting and running in of the measurement system. Getting used to the equipment took some time, and a number of problems had to be solved.

While most of the problems were rather trivial, a few needed some consideration to be solved. A number of the ground based channels and the analog telemetry system had a built-in span check capability, which in principle circumvents the zero-adjustment and gain-control problem, but the digital telemetry system did not have that feature. Furthermore the long term stability of the strain-gauge installations was not considered sufficient to allow the measurements to be referred to zero measurements made in periods with zero wind speed, and it was therefore necessary to establish zero measurement procedures to be applied in conjunction with the measurements taken in operational wind. The problem of referring the measurements to a force-free condition was then transferred to the data evaluation phase. This problem is substantial since in addition to the wind forces during zero measurements also the gravity forces are difficult to account for because the rotor assembly is statically indeterminate.

It was essential to choose proper amplifications and zero settings for the digital telemetry in order to utilize the limited range of 255 counts optimally. However, this proved to be a minor problem which was solved during a few initial runs.

Serious problems, however, were experienced with the wireless telemetry systems. The FM link of the analog telemetry system had so severe problems with noise, that it was decided to concentrate the efforts on the digital telemetry system only. This suffered from problems with mechanical fatigue of components such as print cards due to the gravity field, that rotated relative to the instrument. This problem was solved by reinforcing the components mechanically, but problems with spikes and interruptions of signals proved more difficult to solve. Following some electronic refinements (floating zero, shielding etc.) the remaining spikes were removed by securing a connection between sender and reciever, that was uninterrupted by stays and other obstacles.

Other, minor problems were to make the nacelle instrumentation oil-tight and to protect the external equipment against the rough environment. As the instrumentation was gradually run in an increasing problem proved to be that of keeping the working channels intact. This problem was not diminished by a distance of 150 kilometers to the mill.

Fig. 4.3 shows the preamplifiers being adjusted on the rotor. It was a tough job, and during winter times hot coffee proved essential in keeping the personnel intact.

The measurement procedures developed during the initial phase of the measurements are outlined in fig. 4.4. The runs were recorded during sessions of 2-5 days duration. As the measurements proceeded, more specific demands for the weather conditions arose,and obtaining reliable weather forecasts showed to be a major problem.

During a typical session 1 to 3 runs were recorded. Most of the first day of a session typically was spent warming up the instrumentation, i.e. checking/repairing channels, zero adjusting rotor channels etc. A typical run then was initiated, when desired wind conditions arose. The channel signals were checked using paper writers, and with stopped mill static zero and span check readings were made. Static zero readings includes both wind and gravity forces. During upstart (typically 2-5 min. duration) dynamic zero readings were made on a separate data file. Dynamic zero measurements are averages over one slow revolution (typically 20 sec. duration) and gravity forces thus are averaged out. When the mill had coupled to the grid recordings were not started before all channel signals had been checked using paper writers. When the recording was terminated and the mill was stopped, static zero measurements might be made.

Usually the measurements were made by a team of 5 plus a utility representative operating the mill. A major part of the maintenance and repair work was done by the team between runs.

Finally, fig. 4.5 and 4.6 show examples on data after processing, that consists mainly in cleaning the records by replacing faulty scans with the previous scan. Only some of the pulse counting channels have demanded more elaborate editing, an example being the rotor velocity. The signals generally show satisfactory resolution.

5. Experiences

Fig. 5.1 contains a summary of the major problems encountered with the instrumentation and precautions made to their solution.

As part of the instrumentation and recording equipment were prototypes, and other parts originally designed for other purposes and now applied for the first time under these rather extreme measuring conditions, extensive commissioning tests and modifications showed necessary before start of field measurements.

The sensor themselves have presented few problems, that mostly have been associated with non-standard sensors. The externally mounted straingauges were stable, although some decay of isolation resistances was observed towards the end of the measurement period.

The strain gauge preamplifiers purchased for the digital telemetry system had to be returned twice because laboratory testing showed that they were not up to specifications. Once the amplifiers were replaced there have been few problems with the strain gauges except for the not surprising finding that any cable near the amplifiers should be left where they are, as otherwise small changes in currents in the cables immediately necessitate a new, complete readjustment of all amplifiers.

The main problems experienced have been in the wireless data transmission, which have caused a considerable delay in the program schedule. After completion of the set up of the whole system all signals from the rotor showed up to be faulty. The digital telemetry system showed several spikes on each rotor revolution. The problems were finally solved by mounting the transmitter antenna on the protruding tip of the stay assembly and by moving the receiver antenna approx. 100 m away from the mill in a suitable direction. The radio link was quite sensitive to the position of the receiving antenna, which had to be repositioned before every run depending on the wind and rotor directions. There have been no serious problems in finding the right positions for the receiving antenna. It also showed up that the digital telemetry system was never designed to be vibration resistant. In several instances broken print cards have had to be repaired and improved in order to resist the rough environment. The Aanderaa and bus recording systems which were connected directly to the sensors by cables have given no problems worth mentioning.

The digital transmission of data has proved reliable. Distortion of signals seem to be to a large extent detectable, and this type of transmission contains a kind of redundancy, because faulty scans in many cases may be restablished during processing on basis of the regularity of the bit patterns. Thus this type of transmission appears as a robust data transmission.

The accuracy estimates made on the results indicate, that the deviations of the results from the sensors as it is desirable are only marginally increased by the data transmission and recording equipment. However, in some analog signals having small resolution the digitizing may add significantly to the deviations, and this is also the case for pulse counting channels giving few pulses per scan. This is a disadvantage associated with digital transmission/recording, but it may be overcome with more careful matching of the sensors and the recording system. This was in fact done with the pulse counting signals half way through the measurements by conversion into measurements of time lag between the pulses. The time lag was recorded by recording the number of pulses from a 100 kHz oscillator arriving between sensor pulses. This effectively reduced the digitizing error on these channels.

Fig. 5.2 contains a summary of the experiences with the measurement procedures and the strategy adopted for the measurements.

With the instrumentation at hand the remote processing of tape recorded data was given, and it was chosen to record all channels in every run. Given that initial choise the execution of the measurements during few concentrated sessions still seems appropriate, because the instrumentation when zero adjusted and checked proved reasonably stable during the next few days.

However, the choice of measuring all channels in every run is not obviously correct. Although the most complete overall picture of the mill in principle is obtained this way, the practical difficulties connected with keeping all channels intact all the time proved to be very large indeed.

Problems of another kind have appeared as a consequence of the fact that the measurements have been made without actual analysis being performed in parallel to the measurements. For various reasons the analysis was not included in the contract, which means that the control of the data rests on spot checks only, while the control and feed-back to the measurements associated with the data being applyed in analysis and model verification is missing. Therefore the amount of data, that may confidently be used in analysis is lesser than what might have been obtained. However, a very large amount of data is recorded, and the real problem now is not, that there are too few reliable data but rather, that the extraction of valid data from a total of 17 hours of records demands considerable efforts.

The procedures for the execution of runs have worked reasonably well, considering the large number of channels of different types. During most of the sessions rather high windspeeds were aimed at, and consequently runs had to be made when the high winds occurred, leaving limited time for rigorous checking of the channels before the runs. Therefore the sensors were given precedence according to their importance so that the most important channels were checked first during the check phase before the runs.

All measurements have been made by the same team of 5 people responsible for both recording and data processing, although runs have been made by as few as 2 people. This continuity proved extremely profitable both in the maintenance of the equipment and in the recording, processing and control of the data. The increased personal experience and familiarity with the measurement system without any doubt is the main reason for the increased reliability of the system and the recorded data experienced during the measurement period.

6. Conclusions

The measurement system used in the Gedser measurements was to a large extent based on equipment available at the time, and it appears from the preceeding parts, that it was certainly not free from troubles. Nevertheless it performed in fact satisfactory in many ways, and the records seem to contain sufficient data for meaningful analysis. Fig. 6.1 summarizes the most important experiences that may be of interest for the layout of future wind mill measurements.

Standard off-the-shelf sensors and equipment may very well perform satisfactorily, and they should be preferred when available. It is however advisable that they be checked in the laboratory in order to secure that they meet the specifications expecially regarding stability, since this may be extremely difficult to check when mounted on the mill.

After initial troubles the transmission of data from rotating parts using digital wireless telemetry proved reliable. It seems that such antenna systems very well may have problems during the running-in phase, but that they then will perform well. We feel that digital radio transmission of data may be trusted in the sense, that signal errors most often will have their origin elsewhere in the system.

The digital recording of data which is natural in connection with digital data transmission seems advantageous for the reasons given above. However, problems of accuracy may occur in connection with pulse counting channels, but these problems may be overcome by a time measuring gate and possibly a better digital resolution of the digitizer. This may be of general interest for example in the high speed recording of cup-anemometer signals, that very often are pulse counters with a fairly slow pulse rate.

Although the instrumentation was reasonably stable during the sessions, long term stability of the instrumentation caused considerable problems, and much effort was offered in order to keep instrumentation drift under control and to control proper sensor functions. We feel that a span check function to be applied as close as possible to the sensor should have a high priority.

The strategy adopted of measuring all channels during all runs posed considerable problems. It demanded much effort to secure proper operation of all channels at all times, and the effort was not entirely successful. We feel that it might be advantageous to concentrate on specific effects in a given run.

The strategy adopted of making all measurements before analysis is commenced poses problems, since it may be difficult to know when to have confidence in the results. We feel that instead of recording vast amounts of data in this way it may prove profitable to make a limited amount of recordings, each recording being preceeded by preliminary estimates of what to expect from the records. This greatly will facilitate the data control and thus improve the confidence of the data.

The strategy adopted of using the same team for field measurements and data processing appears to be necessary, when remote data processing is made. This is a function of the problems mentioned above, since the confidence to be associated with the data recorded at Gedser is dependant of a close knowledge of the actual behaviour of the instrumentation. If, however, the procedures outlined above are followed we feel that on-line processing in this context may lead to the data processing being more independent of the data recording, although we still feel, that the possibility of remote date processing af runs on basis of recorded tapes should be retained.

In short, the measurement system at Gedser performed satisfactorily in may ways, but running-in of the system, current maintenance and stability control of the system caused the majority of the problems and most of the effort was used on this. Needs for improvements are apparent just as much in the strategies for the use of the system as in the system itself.

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MEASUREMENT PROGRAM

THE GEDSER MILL

PURPOSE

PROGRAM

MEASUREMENT SYSTEM

SENSORS

DATA TRANSMISSION

RECORDING

MEASUREMENT PROCEDURES

RUNNING-IN OF THE SYSTEM

MEASUREMENT SESSIONS

EXPERIENCES

INSTRUMENTATION

PROCEDURES

CONCLUSIONS

Fig. 1.1

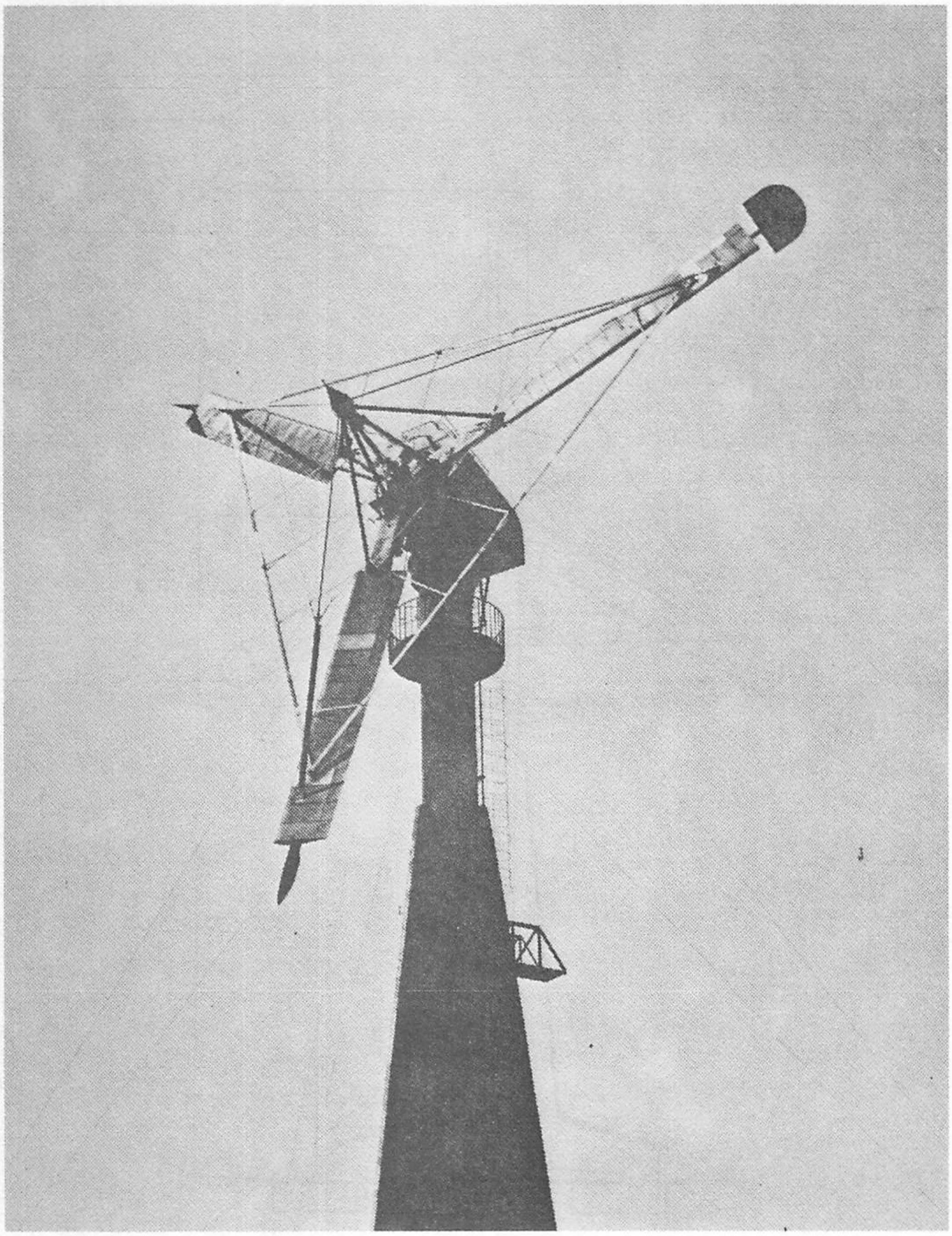


Fig. 2.1

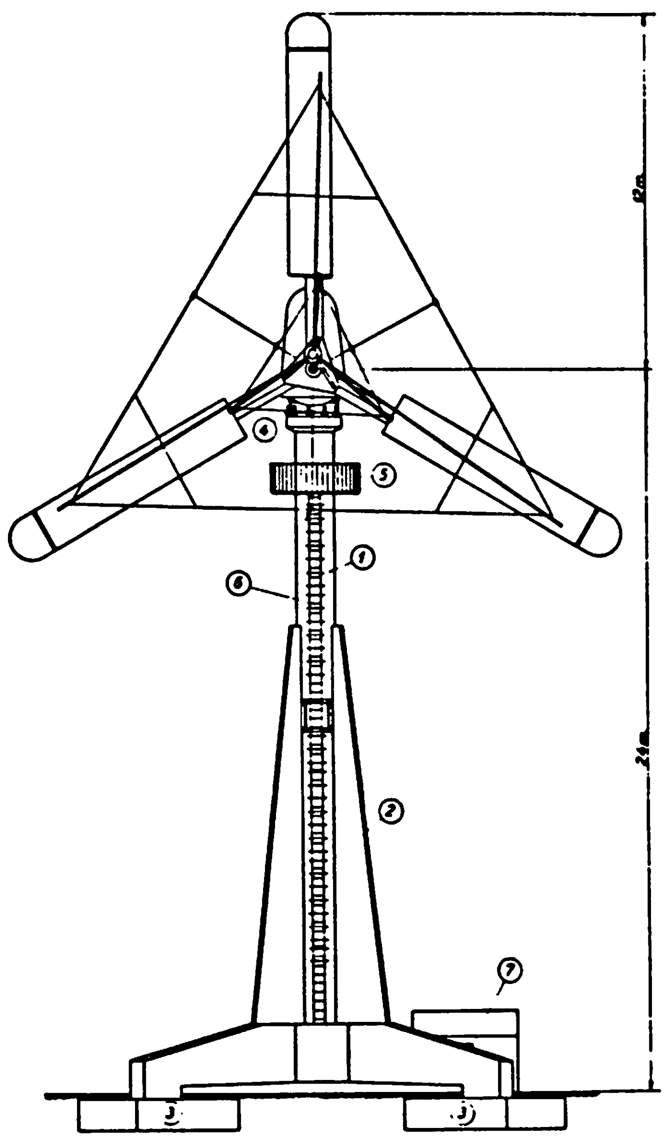


Fig. 2.2. The Gedser windmill

1 Vertical tube of the tower
2 Buttresses
3 Foundation
4 Measuring cylinder
5 Service platform
6 External ladder
7 Transformer house.

Rotor location	Upwind
Rotor diameter	24 m
Number of blades	3
Blade tip velocity	38 m/s
Rotational velocity	30.23 rpm at zero slip
Rotor area	450 m^2
Blade construction	Steel, main spar, wooden webs, aluminium skin. Heavily stayed. Braking flaps in blade tips
Regulation	Stall regulated, no pitch control
Generator	Asyncroneous 200 kW, 750 rpm (1% slip at 200 kW)
Transmission	Double chain 1:24.84 (primary 1:4.74, secondary 1:5.24)
Tower	Stiffened concrete cylinder, hub height 24 m
Performance	Selfstarting at 5 m/s 200 kW at 15 m/s Typical annual production 350.000 kWh/yr (ref.1)

Fig. 2.3

AIMS OF THE MEASUREMENTS:

- DETERMINATION OF POWER/WIND RELATIONSHIP
- DETERMINATION OF LOADS AND STRUCTURAL RESPONSE
- INVESTIGATIONS OF POWER, FLUCTUATIONS
- DATA FOR LATER MODEL VERIFICATION
- DATA FOR COMPARISON WITH MODERN MILLS

Fig. 2.4

MEASUREMENT PROGRAM:

METEOROLOGICAL MEASUREMENTS

- LONG TERM
- SHORT TERM

POWER MEASUREMENTS

- CHARACTERISTICS
- FLUCTUATIONS

STRUCTURAL RESPONSE MEASUREMENTS

- ROTOR FORCES AND MOMENTS
- NACELLE FORCES AND MOMENTS
- NACELLE MOVEMENTS

EXECUTION:

LONG TERM MEAS:

CONTINUOUS 10 MIN. AVERAGES

SHORT TERM MEAS:

FAST SAMPLING OF ALL CHANNELS

RUNS RECORDED ON TAPE

REMOTE DATA PROCESSING

Fig. 2.5

Group	Number of Channels	Transducers	Quantities measured
1	21	Strain gauge sensors on blade 3 and adjacent stays	Blade section forces and stay forces
2	5	Differential pressure transducers on blade 3	Differential pressures on blade 3
3	19	Strain gauge sensors on blade 2 and adjacent stays	Blade section forces and stay forces
4	5	Strain gauge sensors on measuring cylinder	Forces between nacelle and tower top
5	4	Accelerometers in nacelle	Linear and angular accelerations, yaw rate
6	3	Pulse counters and potentiometer in nacelle	Rotor positions (1/1^{o} and 1/360^{o}) and nacelle position
7	2	Strain gauge sensors on transmission shafts	Transmission and generator shaft torque
8	3	Electrical power transducers	KWATT, KVAR and Volt
9	12	Ultrasonic anemometer sensors	Wind vector and temperature at 3 levels
10	9	Various sensor	Meterological wind condition data
11	2	Anemometer and wind vane	Wind speed and direction at hub heigth

Strain Gauges:	Cement	Hottinger X60, Eastman 910
	Moisture protection:	Silicagel Philips PR 9258/00
		Neoprene foam rubber
		Glass fabric

Fig. 3.1

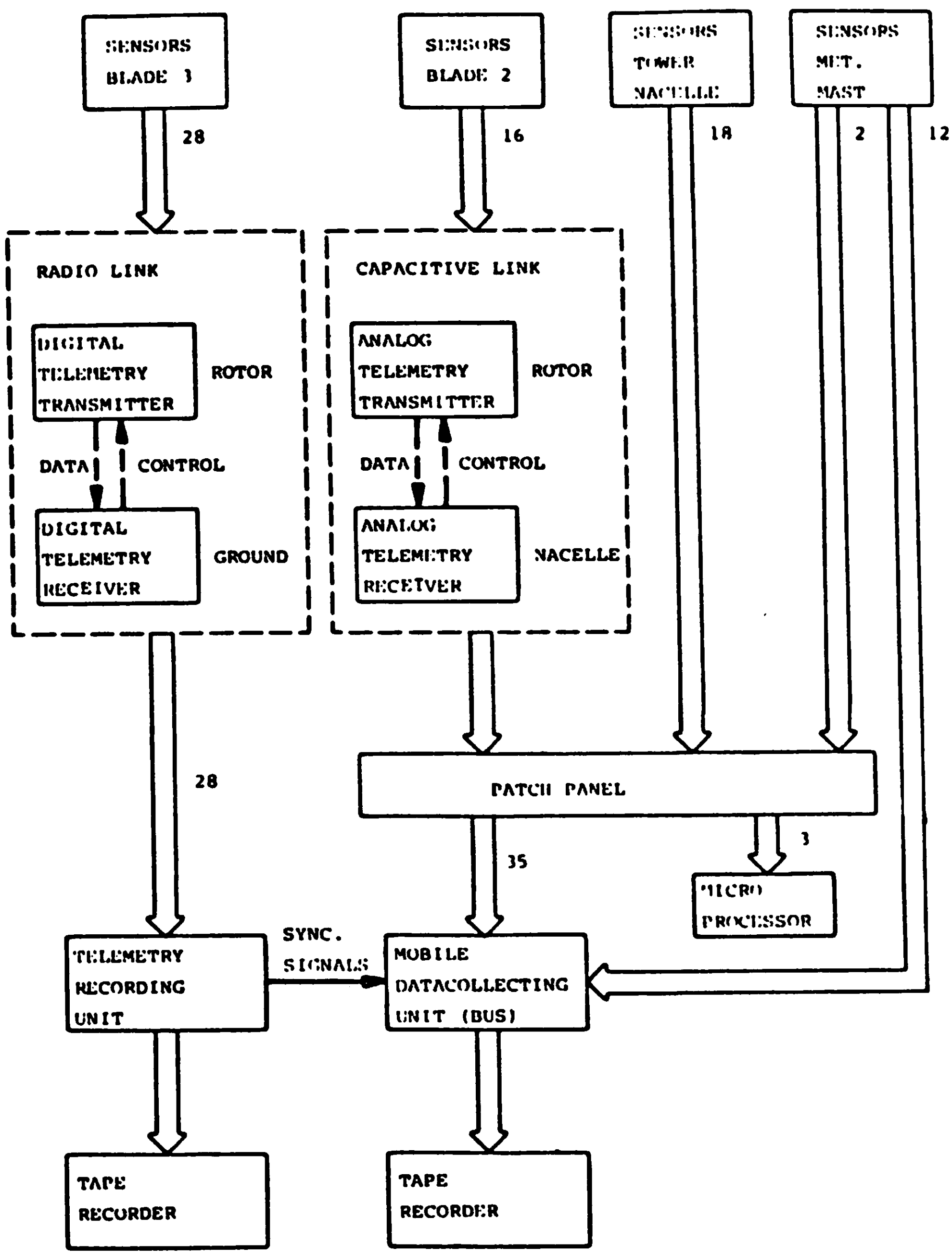


Fig. 3.2. Diagram for the data flow during short term measurements.

SPECIFICATIONS	TELE	BUS
CHANNELS	28	60
TRANSMISSION	27GHZ	CABLES
	DIGITAL	ANALOG
RECORDING	DIGITAL	DIGITAL
RESOLUTION	256	4096
SAMPLING	SERIAL	AVERAGE
AMPLIFICATION	+	+
SEPARATE RECORDER	+	+
PAPER WRITER	-	+
SPAN CHECK	-	+

Fig. 3.3

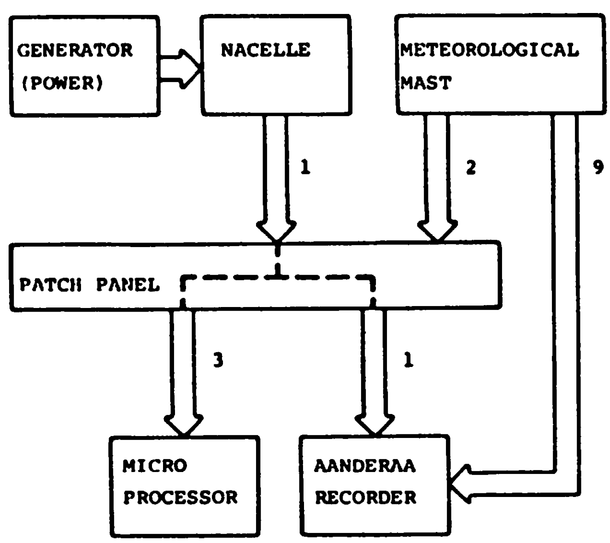

GENERATOR
(POWER)
NACELLE
METEOROLOGICAL
MAST
1
2
9
PATCH PANEL
3
1
MICRO
PROCESSOR
AANDERAA
RECORDER

Fig. 3.4

DATA PROCESSING:

TAPES	9 TRK, 800 BPI, 1800 FT
CAPACITY	100.000 SCANS ∿ 5 DECADES
FREQ.CUTOFF	5-25 HZ
SYNC.	TELE SCANNUMBER RECORDED B4 BUS B 6700
PROCESSING	MERGING OF FILES CLEANING THE RECORDS ZERO CORRECTION CONVERSION/CALIBRATION CHECKING
AVAILABILITY	PROCESSED RUNS AS RAW DATA ON 2 TAPES + CONVERSION ROUTINE

Fig. 3.5

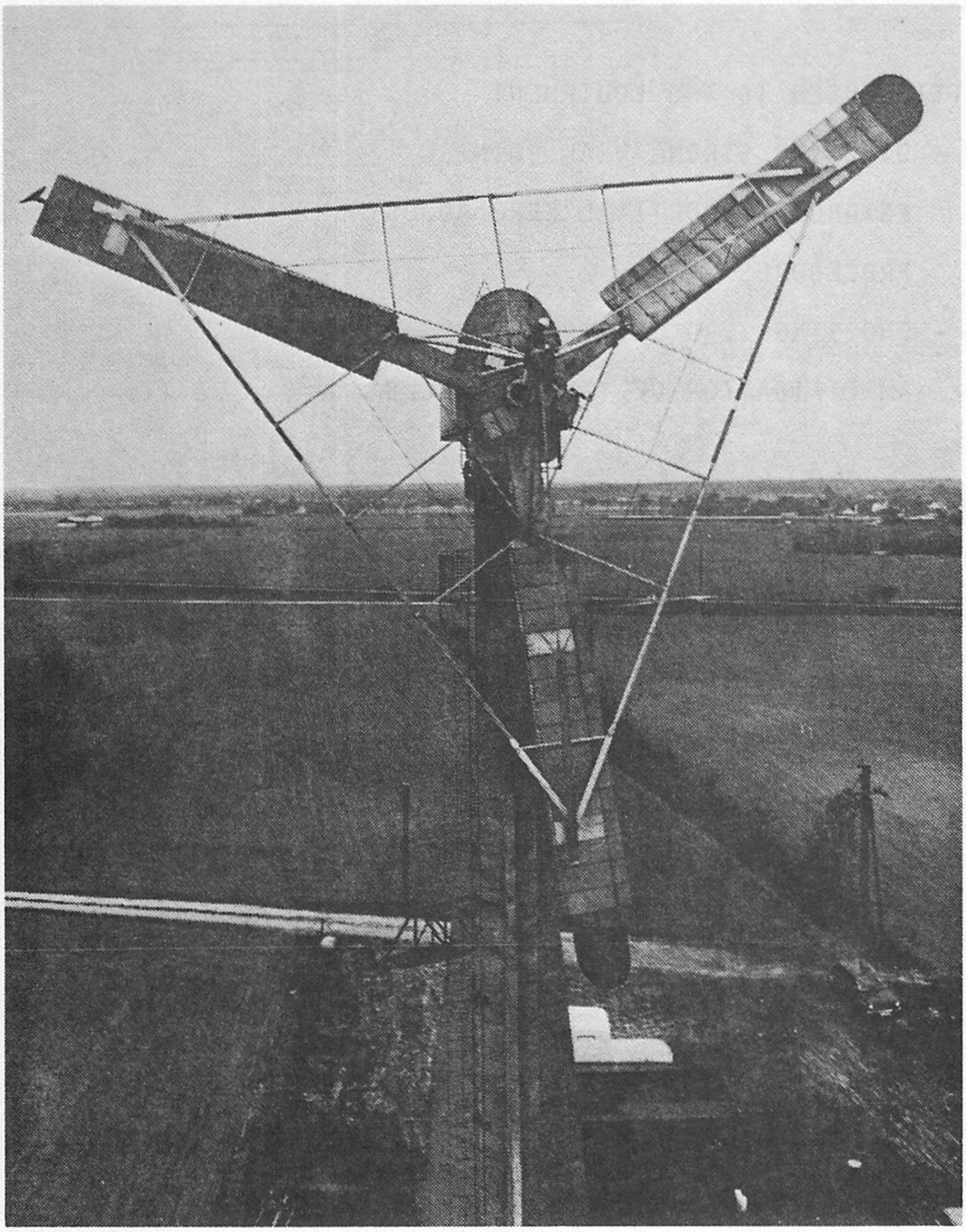


Fig. 4.1

RUNNING-IN OF THE SYSTEM:

GETTING USED TO THE EQUIPMENT

- DISCOVER STRONG/WEAK POINT
- ESTABLISH PROCTICAL ZERO ADJUSTMENT PROCEDURES
- CHOOSING ZERO SETTINGS AND AMPLIFICATION OF TELE CHANNELS

TELEMETRY/TRANSMITTER PROBLEMS

- ROTATING GRAVITY => MECH.FATIGUE
- NOISE ON KHZ LINK (ANALOG TELE)
- SPIKES ON GHZ LINK (DIGITAL TELE)

OTHER PROBLEMS

- MAKING EQUIPMENT OILTIGHT
- EXTERNAL MOUNTING OF EQUIPMENT
- KEEPING WORKING CHANNELS INTACT
- 100 MILES TO THE MILL

FIG. 4.2

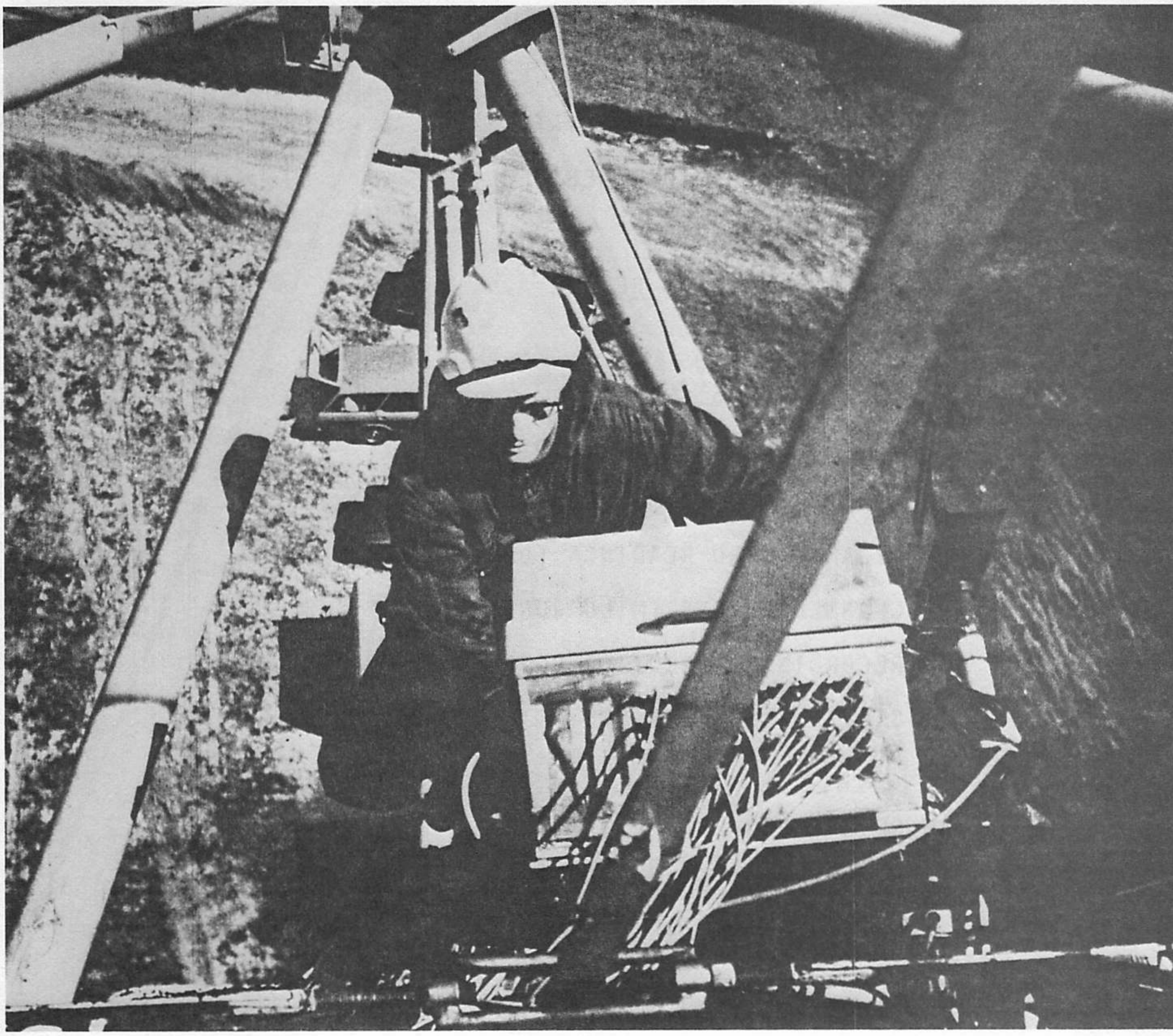


Fig. 4.3

MEASUREMENT PROCEDURES:

SESSIONS OF 2-5 DAYS

- ACTIVATING INSTRUMENTATION
- 1-3 RUNS PROVIDED DESIRED
  WIND CONDITIONS
- MAINTENANCE AND REPAIR

RUNS OF 2-5 HOURS

- CHANNEL CHECKS (STOPPED MILL)
- STATIC ZERO/SPAN CHECK READINGS
- DYNAMIC ZERO READINGS (UPSTART)
- CHANNEL CHECKS (MILL RUNNING)
- RECORDING (APPROX. 1 HOUR)
- STATIC ZERO READINGS

TEAM OF 2-5 PEOPLE

- MEASUREMENTS
- DATA PROCESSING

Fig. 4.4

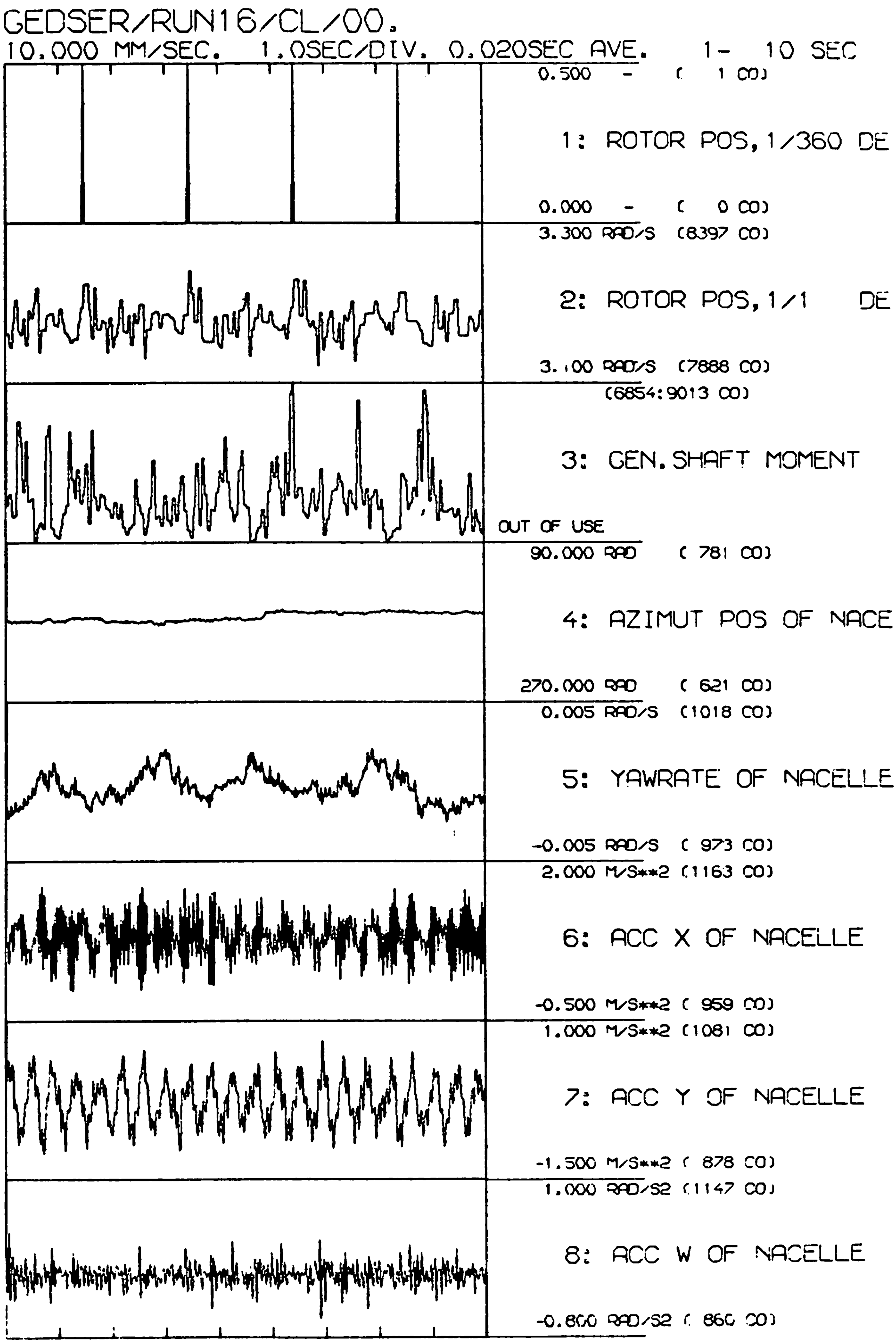

GEDSER/RUN16/CL/00.
10.000 MM/SEC. 1.0SEC/DIV. 0.020SEC AVE. 1- 10 SEC
0.500 - (1 CO)
1: ROTOR POS,1/360 DE
0.000 - (0 CO)
3.300 RAD/S (8397 CO)
2: ROTOR POS,1/1 DE
3.100 RAD/S (7888 CO)
(6854:9013 CO)
3: GEN.SHAFT MOMENT
OUT OF USE
90.000 RAD (781 CO)
4: AZIMUT POS OF NACE
270.000 RAD (621 CO)
0.005 RAD/S (1018 CO)
5: YAWRATE OF NACELLE
-0.005 RAD/S (973 CO)
2.000 M/S**2 (1163 CO)
6: ACC X OF NACELLE
-0.500 M/S**2 (959 CO)
1.000 M/S**2 (1081 CO)
7: ACC Y OF NACELLE
-1.500 M/S**2 (878 CO)
1.000 RAD/S2 (1147 CO)
8: ACC W OF NACELLE
-0.800 RAD/S2 (860 CO)

Fig. 4.5

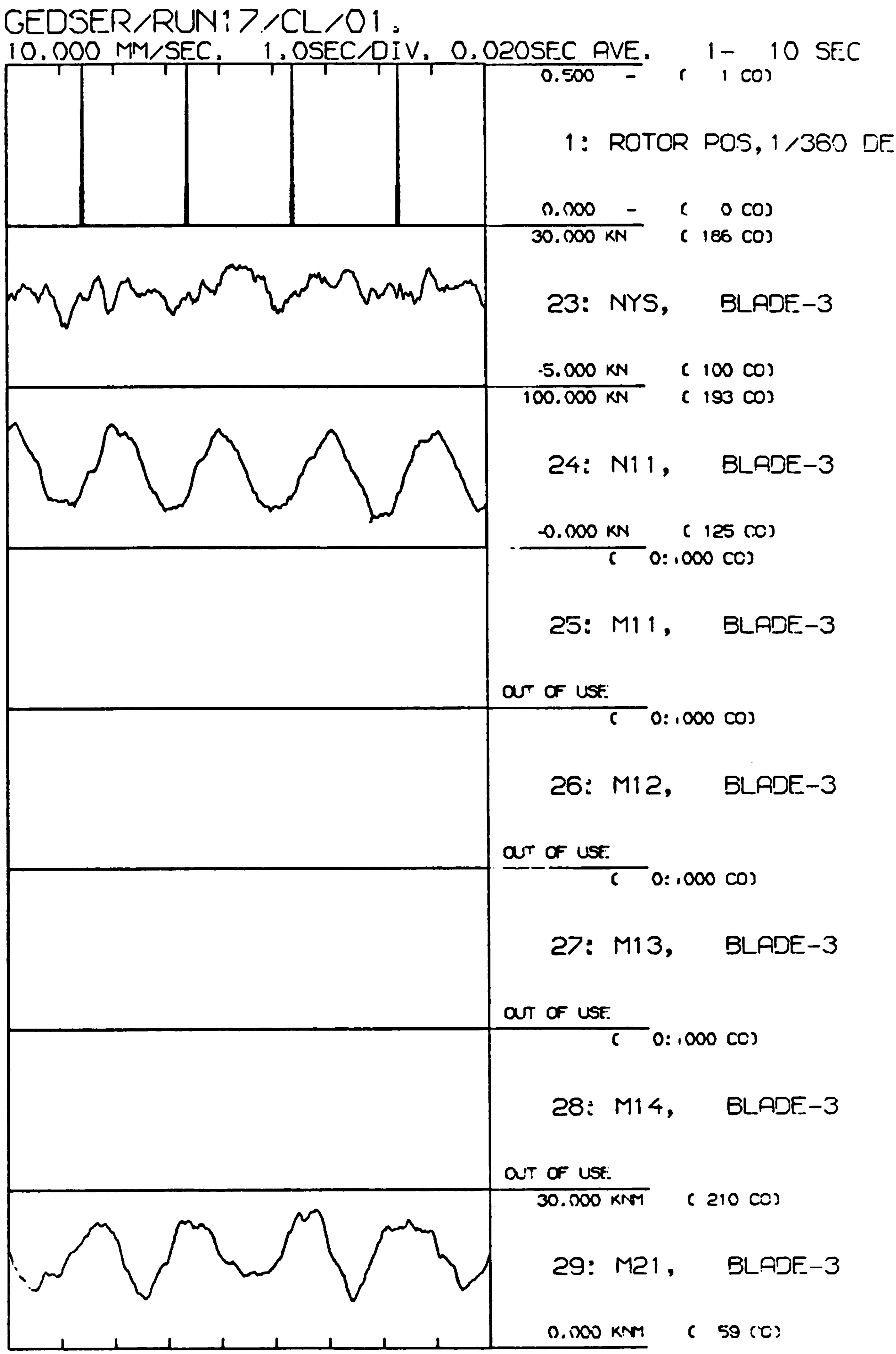

GEDSER/RUN17/CL/01.
10.000 MM/SEC. 1.0SEC/DIV. 0.020SEC AVE. 1- 10 SEC
0.500 - (1 CO)
1: ROTOR POS,1/360 DE
0.000 - (0 CO)
30.000 KN (186 CO)
23: NYS, BLADE-3
-5.000 KN (100 CO)
100.000 KN (193 CO)
24: N11, BLADE-3
-0.000 KN (125 CO)
(0:1000 CO)
25: M11, BLADE-3
OUT OF USE
(0:1000 CO)
26: M12, BLADE-3
OUT OF USE
(0:1000 CO)
27: M13, BLADE-3
OUT OF USE
(0:1000 CO)
28: M14, BLADE-3
OUT OF USE
30.000 KNM (210 CO)
29: M21, BLADE-3
0.000 KNM (59 CO)

Fig. 4.6

EXPERIENCES, INSTRUMENTATION:

- PROTOTYPE INSTRUMENTATION PROLONGED RUNNING-IN PERIOD.

- MOST SENSOR PROBLEMS WITH NON-STANDARD SENSORS, STRAING. STABLE.

- AMPLIFIERS NOT ZERO STABLE AND SENSITIVE TO CABLE MOVEMENTS.

- RADIO LINK SENSITIVE TO REFLECTIONS ETC.
  TELEMETRY VIBRATION SENSITIVE.

- DIGITAL DATA TRANSMISSION AND RECORDING PROVED RELIABLE.

- UNCERTAINTIES IN RECORDED DATA:
  - SENSOR ERRORS (ANALOG CH.)
  - DIGITIZING ERRORS (PULSE CH.)
    THESE ERRORS MUCH REDUCED BY TIME MEASURING GATES:

Fig. 5.1

EXPERIENCES, PROCEDURES:

- FEW INTENSIVE SESSIONS GIVE THE MOST RELIABLE RESULTS. SUITABLE FOR LONG TERM UNSTABLE SYSTEMS.

- RECORDING ALL CHANNELS ALWAYS GIVE MAINTENANCE PROBLEMS.

- NO PARALLEL ANALYSIS LESSEN THE PERCENTAGE OF RELIABLE RESULTS.

- RUN PROCEDURES SATISFACTORY. SENSOR PRIORITY RANGE DUE TO LIMITED TIME FOR CHANNELS CHECK.

- ONE TEAM FOR MEASUREMENTS AND DATA PROCESSING INCREASED DATA RELIABILITY.

Fig. 5.2

CONCLUSIONS:

- STANDARD SENSORS PREFERABLE, LAB. TESTS OF STABILITY RECOMMENDED.

- WHEN RUN-IN OVER, DIGITAL RADIO TRANSMISSION DO NOT INTRODUCE UNCONTROLLABLE ERRORS.

- DIGITIZING ERRORS ON PULSE SIGNALS (CUPANEMOMETER) MAY BE REDUCED BY TIME MEASURING GATE

- SPAN CHECK DESIRABLE FOR EASY STABILITY AND MALFUNCTION CONTROL.

- RECORDING FEW SENSORS AT A TIME IS RECOMMENDED. CONCENTRATE ON SPECIFIC EFFECTS, ESTIMATED IN ADVANCE

- ONLINE PROCESSING SHOULD HAVE REMOTE PROCESSING OPTIONAL.

Fig. 5.3

IEA Expert Meeting: "Large Wind Energy Systems"

Blowing Rock, N. C. (USA)

September 26 to 27, 1979

GROWIAN TEST PROGRAM

(Objectives of Power Output Measurements)

by

Erich Hau

I. INTRODUCTION

The large Wind Energy Plant GROWIAN is designed as a typical plant with respect to power output and technical design to deliver a considerable contribution to electric power need in the Federal Republic of Germany. This contribution should be achieved by a great number of identical units.

Therefore GROWIAN is planned as a prototyp and not as an experimental plant. On the other hand GROWIAN is of such a size, that a variety of technical problems is involved, which only can be solved experimentally. For this reason it is foreseen to carry out a test program in connection with the qualification phase.

The outline of this test program has recently started. The objectives, the measurement methods and the hardware will be studied in more detail.

This paper describes the objectives of the test program with respect to the power output measurements.

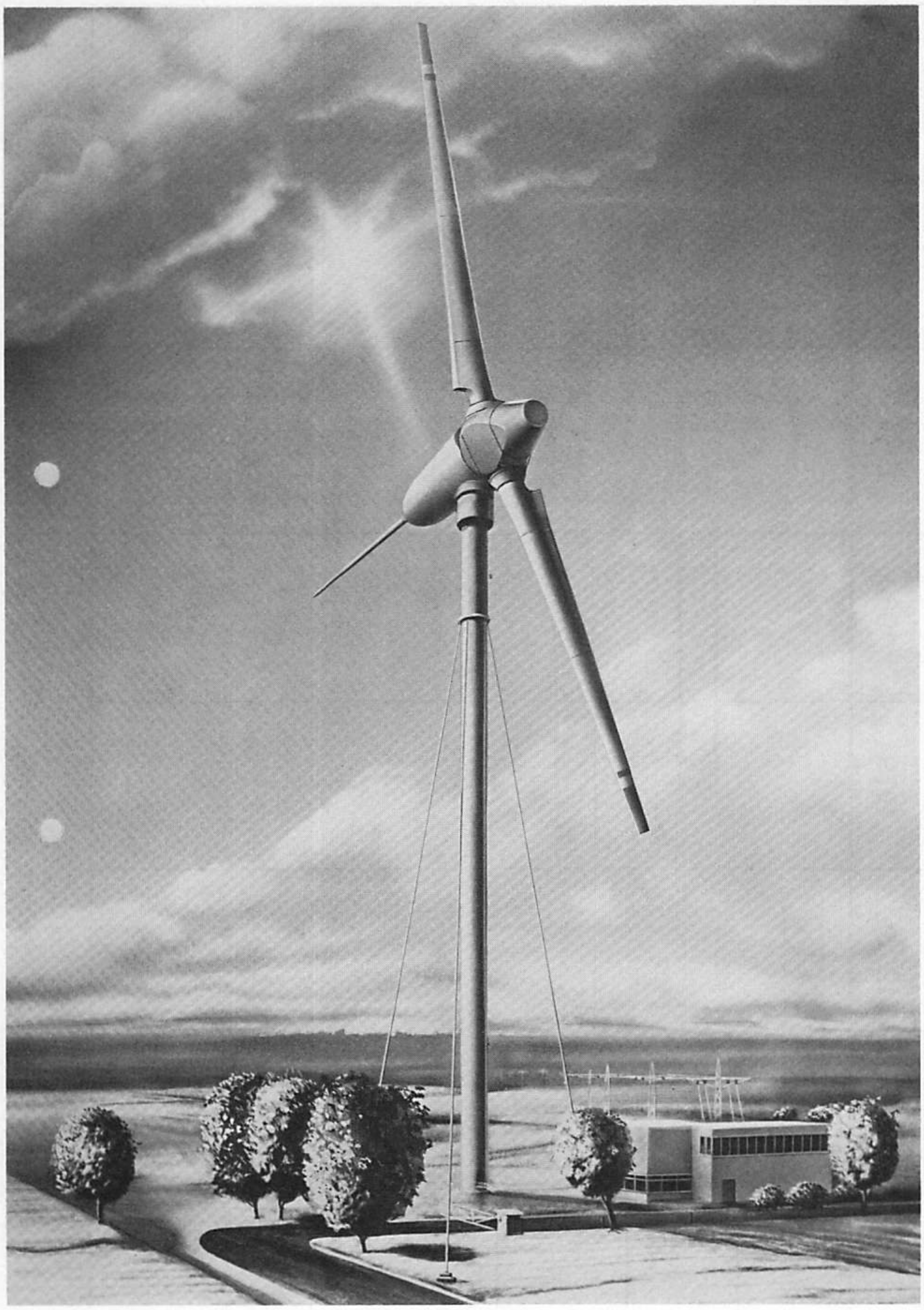
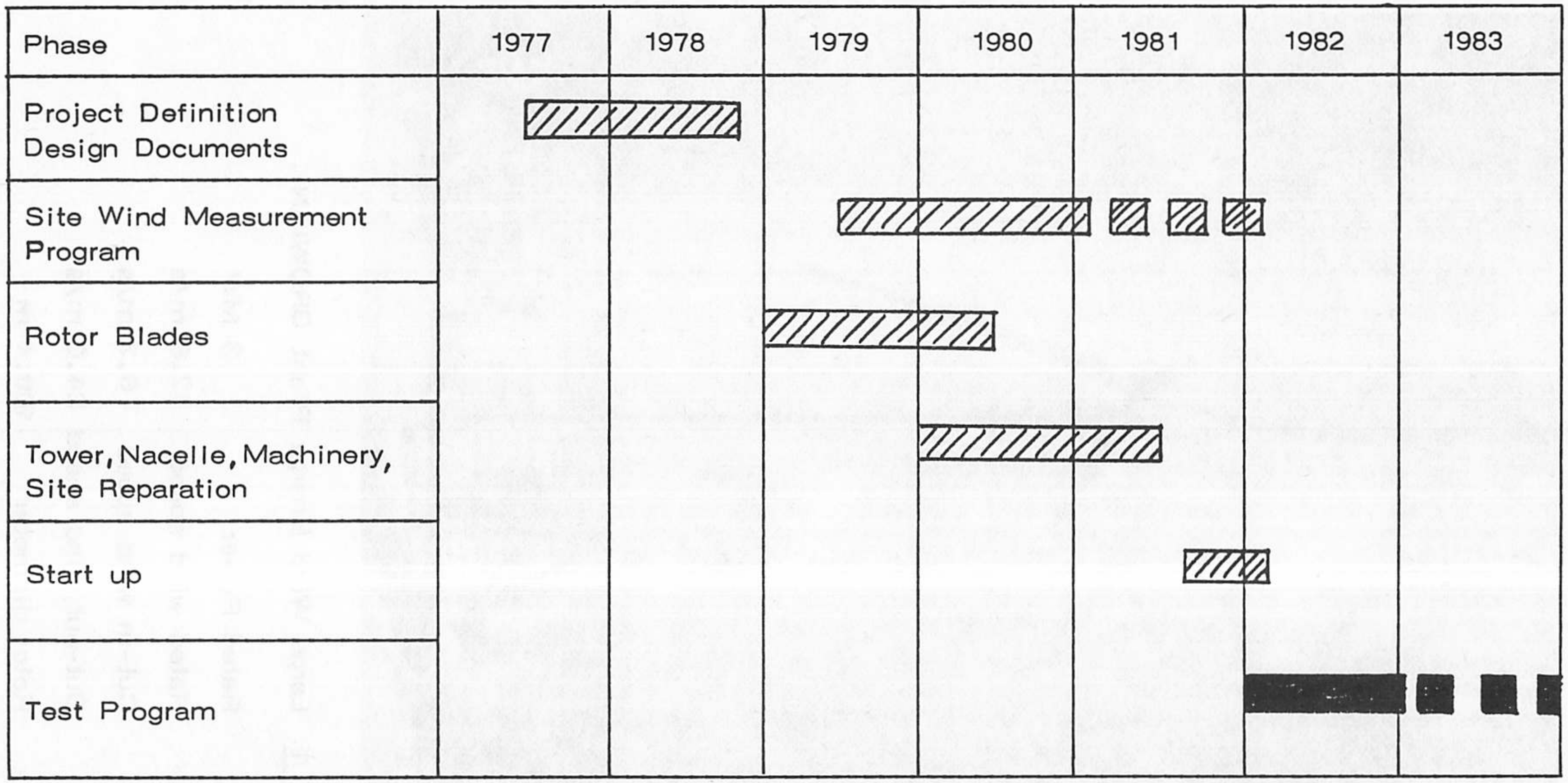


Fig. 1: Large Wind Energy Plant GROWIAN

Rated Power	3 MW
Rated wind speed	12.8 m/s
Cut-in wind speed	6.3 m/s
Cut-out wind speed	24.0 m/s
Rotor diameter	100.4 m
Rotor speed	18.5 rpm ± 15 %
Hub height	100 m

Fig. 2: GROWIAN Program - Time Schedule



II. PREDICTED PERFORMANCES AT THE SELECTED SITE

Site

GROWIAN will be erected in the North German coastal area.
The selected site (Kaiser-Wilhelm-Koog) is about 100 km far away from Hamburg on the mouth of the Elbe river (Fig. 3).
The topography is completely flat with only single groups of trees.

Wind Data from the Site

Up till now wind measurements directly from the site are not available. Therefore a measurement program has been started which takes wind data by means of a special tower of 150 meters height.

These measurements are carried out by the "Institut für Meteorologie und Klimatologie" of the Technical University Hannover. For the performance calculations wind data from the meteorological station of List on the island of Sylt have been taken. These data seem to be somewhat more favourable than the expected values from the site on Kaiser-Wilhelm-Koog.

Figure 4 shows the relative and cumulative frequency of wind speed.

The wind speed at hub height was calculated by means of the Hellmann formula with an exponent of 7.5.

Predicted Performances

Based on the computed rotor performance chart the mechanical power output of the rotor and the generator output have been calculated (Fig. 5).

The curves of Fig. 5 show the performances without consideration of performance losses due to increased surface roughness of the rotor blades, tower shadow or influence of the control system.

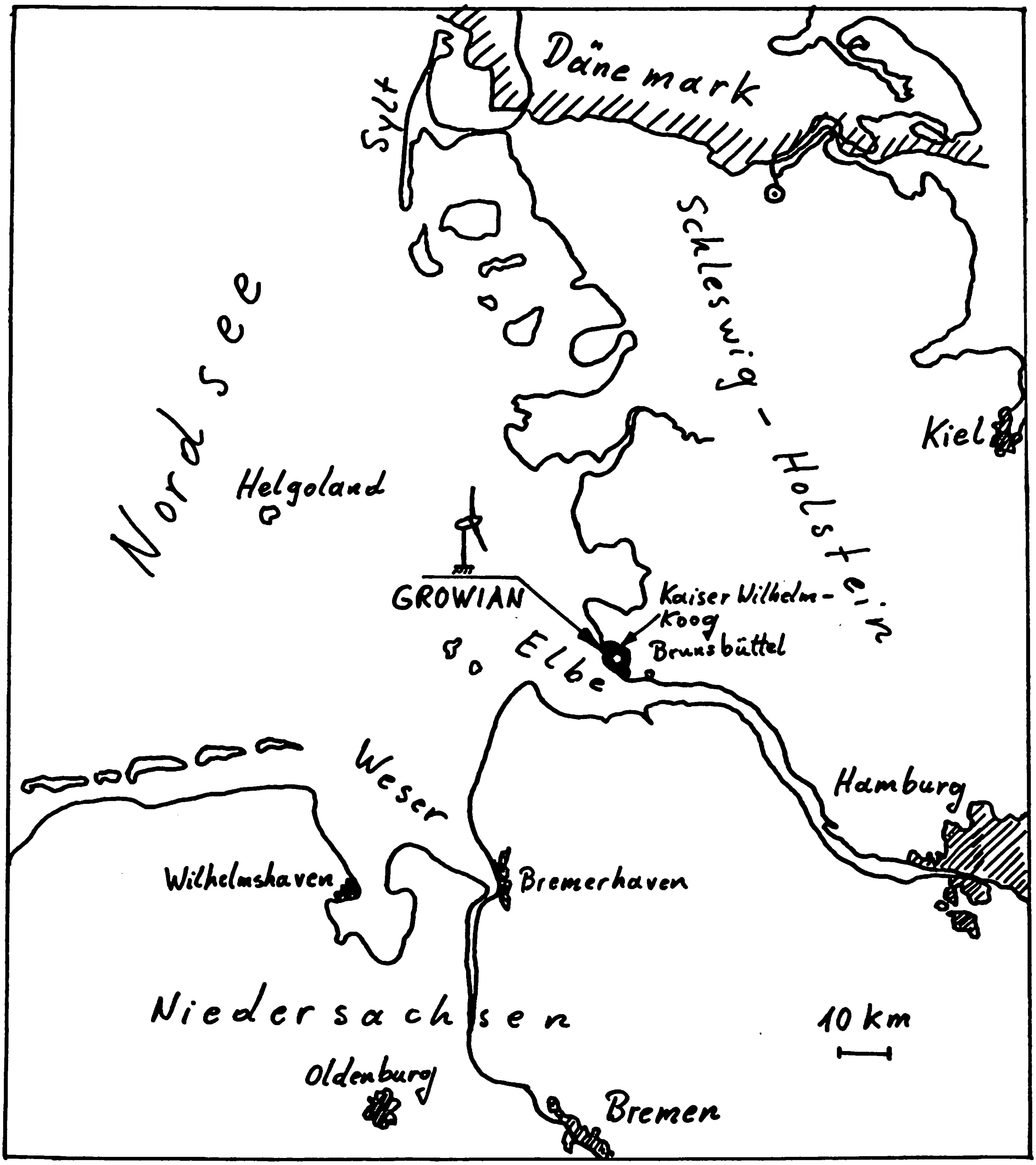
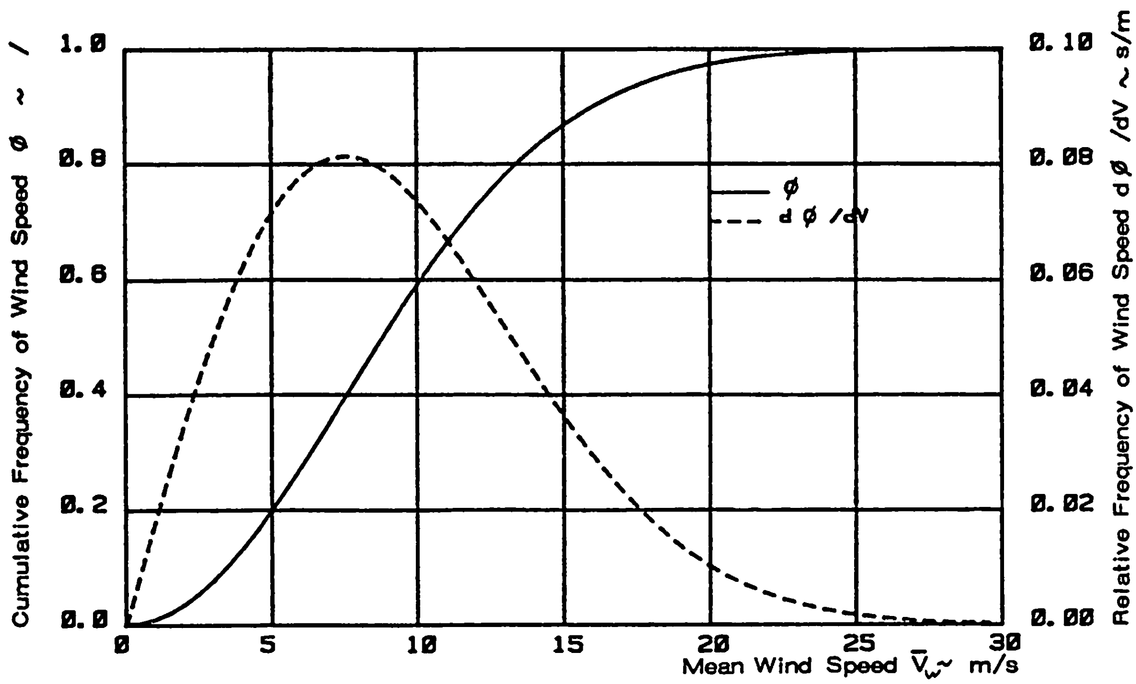
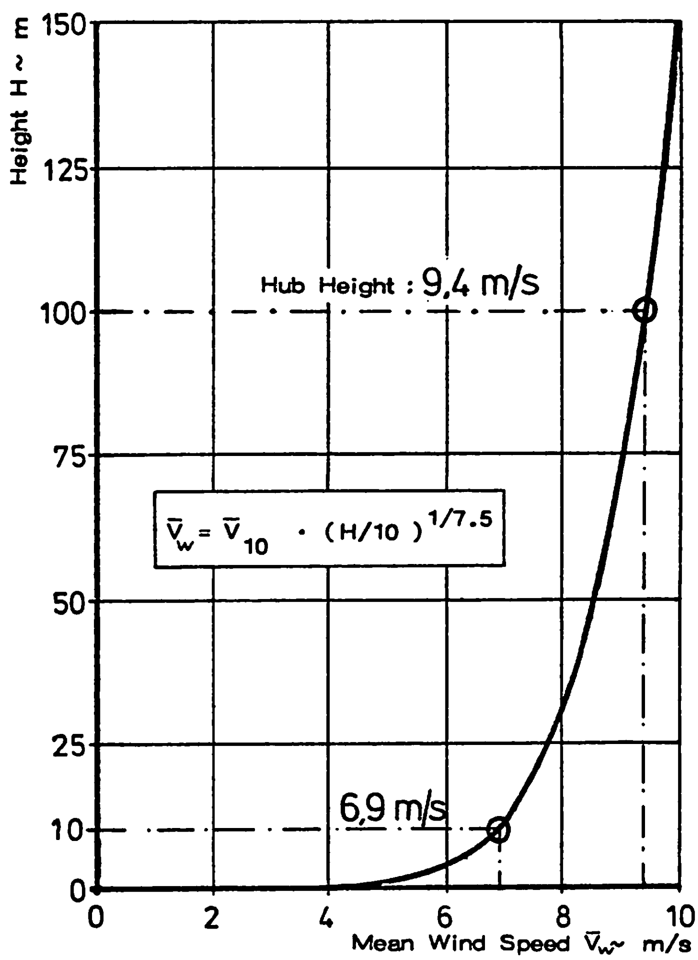


Fig. 3: GROWIAN - Site (Kaiser-Wilhelm-Koog)

Fig. 4 Wind Data

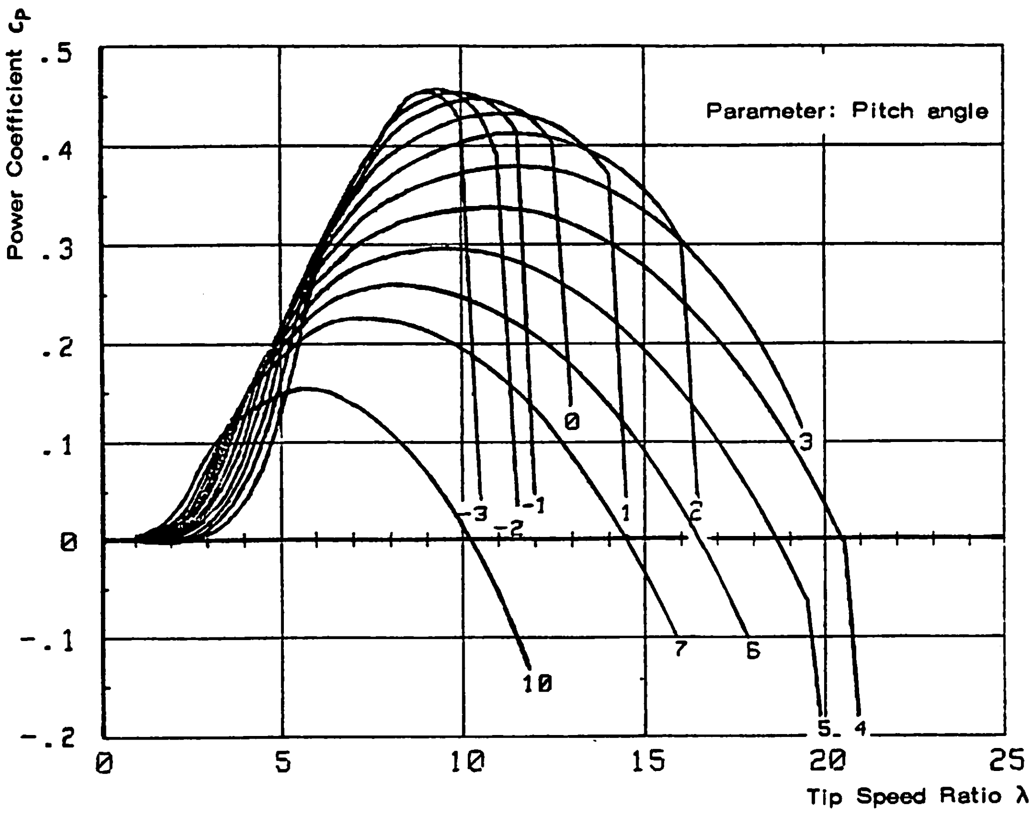


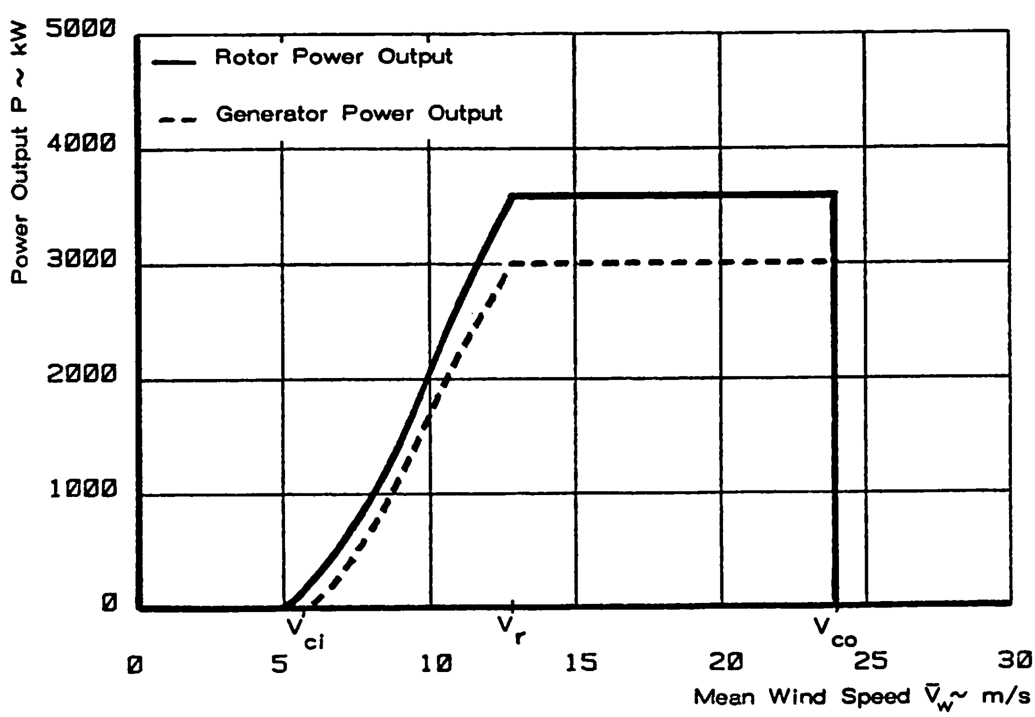
Distribution of Wind Speed for List (Sylt) - W. Germany



Vertical Wind Gradient for List (Sylt) - W. Germany

Fig. 5 Predicted Performances





III. POWER OUTPUT MEASUREMENT PROGRAM

1. General Tasks

The outline of the test program considers two different aims.

For GROWIAN as a prototyp of a commerically used wind power plant a start up test program has to be performed. These tests have to qualify the system and to evaluate the operating modes. For this purpose a permanent operational data acquisition system will be installed.

On the other hand for a limited time GROWIAN has the function of an experimental unit. By means of an engineering data acquisition system a variety of experimental investigations will be carried out. They include modifications of critical components in order to evaluate alternative technical solutions and general tasks of an experimental research program for large wind energy systems.

2. Data Acquisition in Power Measurements

The data acquisition for power output measurements has to consider the special type of generator used. The double feeded asynchronous machine allows a certain speed variation ($\pm$ 15 %) of the rated speed at constant frequency.

The kinetic energy of the rotor acceleration and deceleration has to be taken into account in the correlation between generator output and rotor performance. In order to calculate the rotor power it is necessary to measure the instantaneous rotor speed (ω_{Ro}) and acceleration ($\dot{\omega}_{Ro}$). In that way the rotor efficiency (c_p) can be calculated based on the usual generator output (Fig. 7).

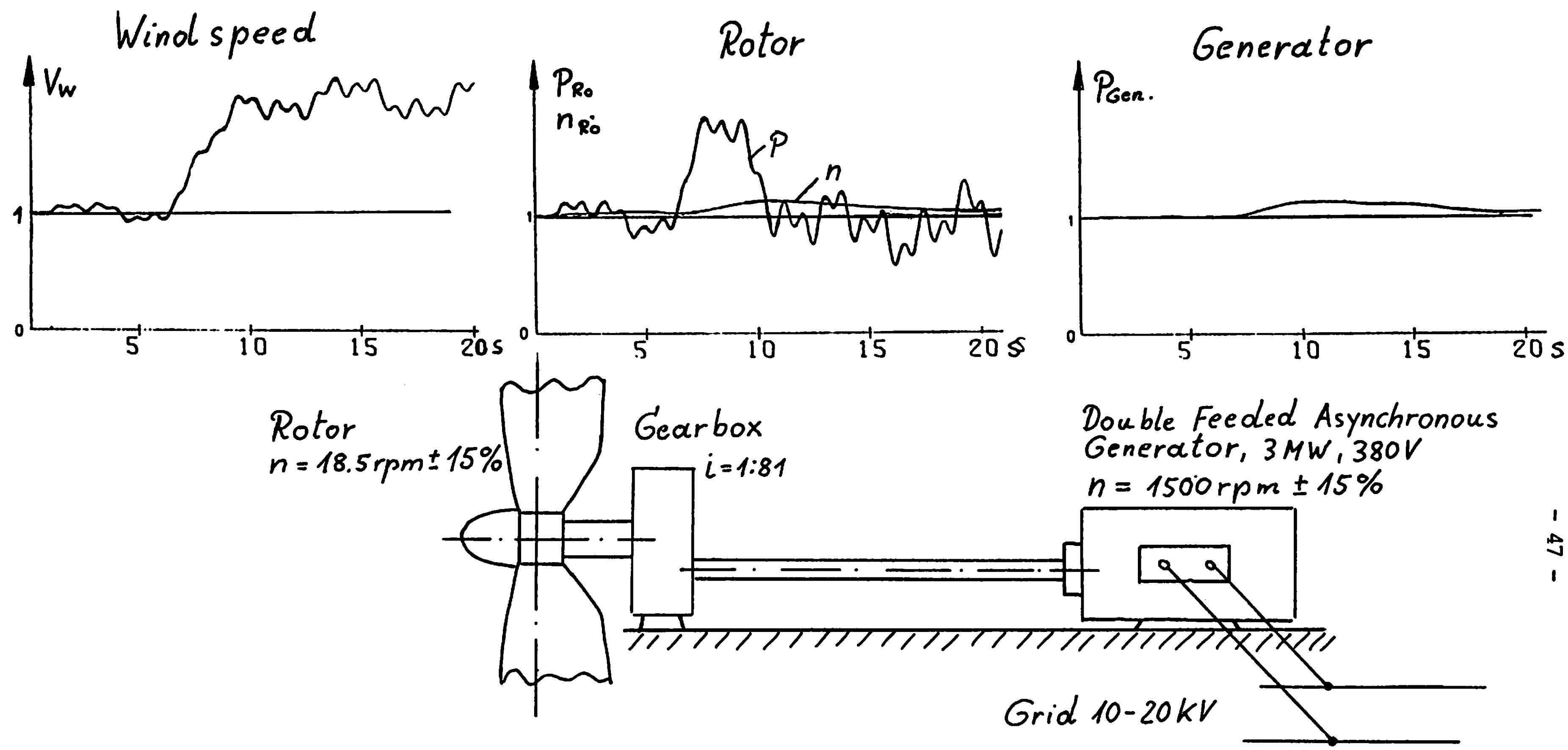
Fig. 6 General Tasks

1. Qualification of the system and evaluation of operating modes

   - GROWIAN as a prototype of a commercially used plant
   - equipped with an operational data acquisition system

2. Testing of alternative design features and experimental research

   - GROWIAN as an experimental unit
   - equipped with an engineering data acquisition system
     (requires additional hardware and design modification)



<u>Mechanical Rotor Power:</u>

measured: $\omega_{Ro}, \dot{\omega}_{Ro}, \bar{V}_W$

to calculate:

$$P_{Ro} = \frac{1}{\eta^*}\left(P_{Gen} + \omega_{Ro}\cdot\dot{\omega}_{Ro}\cdot\Theta^*\right)$$

$$c_p = \frac{P_{Ro}}{\frac{\rho}{2}\, V_W^3 \cdot A_{Ro}} = f\left(\frac{u}{V_W}\right)$$

<u>Electrical Power Output</u>

measured: P_{Gen}

<u>Fig. 7 Data Acquisition</u>

3. Main Objects of the Test Program

Aerodynamic Properties of the Rotor Blade Airfoils

The aerodynamic properties of the chosen laminar flow airfoils decrease significantly with increasing surface roughness.

Figure 8 shows the influence on the power output considering a smooth surface and one with extreme roughness, simulated in wind tunnel tests.

If it proves, that in real operation the surface condition will be near to "rough" some design parameters i. e. the blade pitch angle in partial load operation and eventually the rotor speed have to be changed in order to avoid severe power losses.

In the engineering test program the correlation between blade surface condition and those parameters will be experimentally studied.

Tower Shadow

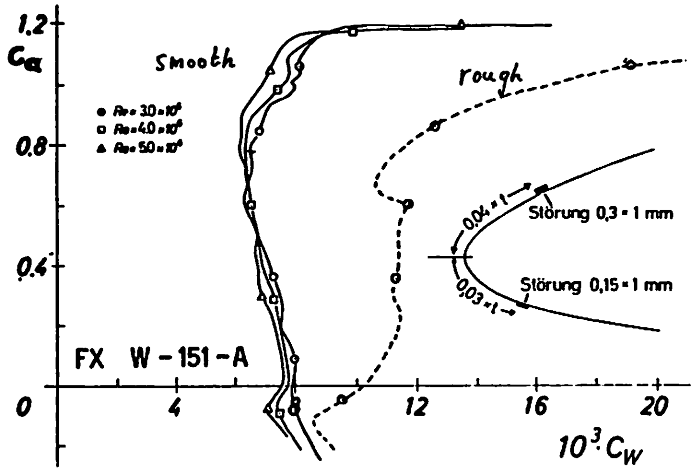
GROWIAN is designed with a leeside mounted rotor. The tower shadow effect is expected to be relatively low due to the slender staged steel tower.

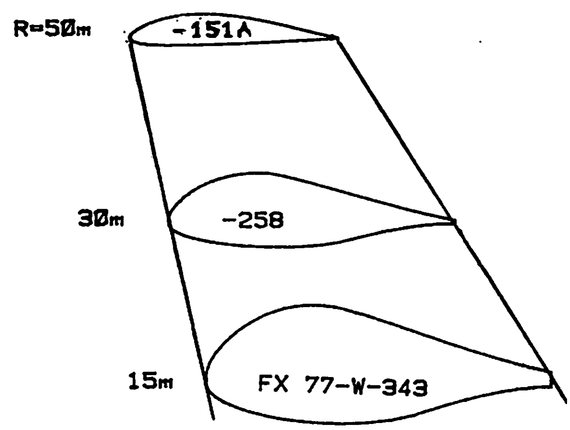
Nevertheless the theoretical calculations show a significant effect on the power output. In the power curve sharp gaps up to 40 % decrease from the steady value could be possible at high operating wind speeds (Figure 9).

The test program with respect to those effects includes the study on power loss and drive train dynamics as well as an evaluation of aerodynamic aids for reducing the tower wake ("vortex generators" (edges) on the tower surface).

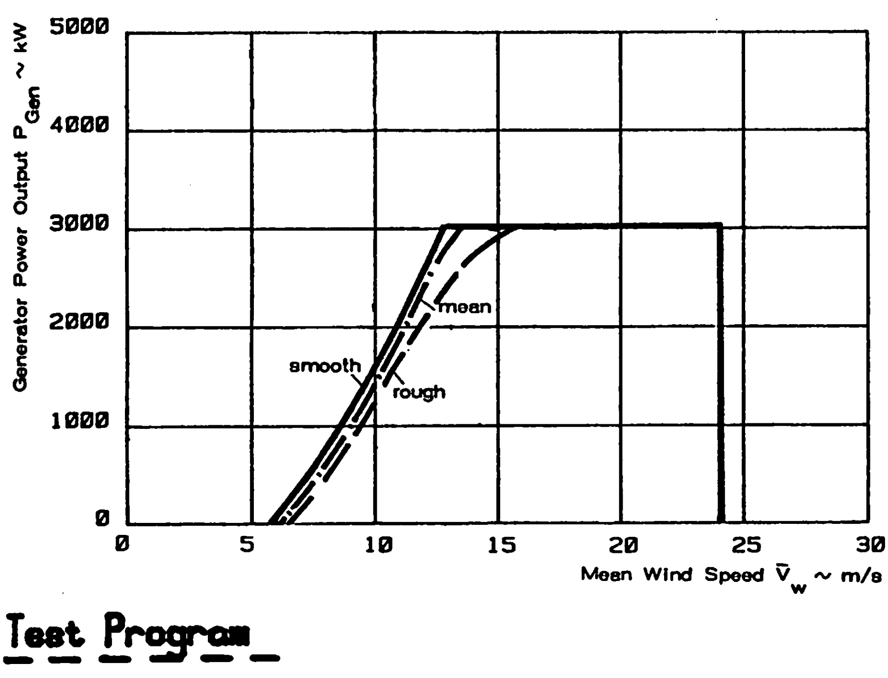
Fig. 8 Aerodynamic Properties of Airfoils (Surface Roughness)

Laminar Airfoils - specially designed for wind turbines by F.X. Wortmann





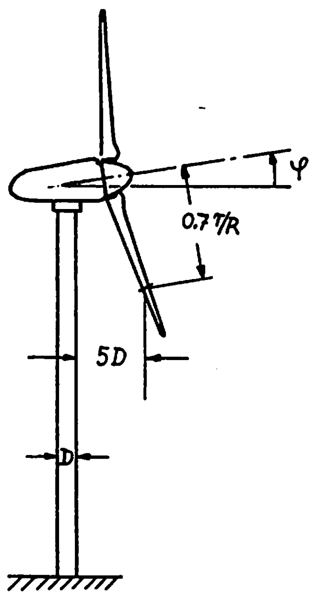
Electric Power Output



Test Program

- Influence of blade surface roughness on power output
- Selection of optimal blade pitch angle and eventually adaption of rotor speed

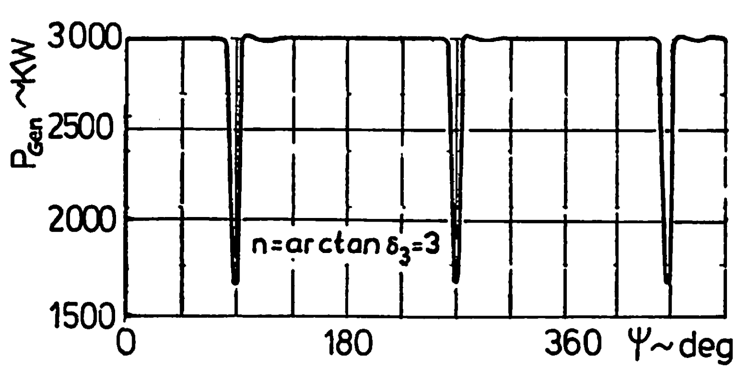
Fig. 9 Tower Shadow



Tower diameter : D = 3.5 m
Tilt angle of rotor axis: φ = 10°
Distance rotor to tower : 5*D

Predicted Influence on Power Output

(according to S. Mickeler)



Test Programm

- Measurement of Tower wake (velocity profile, vortex structure
- Power losses
- Testing of aerodynamic aids for reducing the tower wake ("vortex generators" on the tower)

Power Control

Above rated wind speed the power output is maintained at 3 MW by blade pitch angle variation.

Between cut-in wind and rated wind speed (partial load operation) the pitch angle will be set at a constant position of 2^o. The selection of an optimum constant pitch angle with respect to a maximum power output depends on the characteristics of the rotor performance chart (c_p-λ-chart) (Fig. 10).

That means in the case of degradation due to increasing airfoil roughness the pitch angle has to be changed. In the test program the optimisation of power control in partial load operation will be an important subject. In this framework the feasibility of a control procedure (maintaining the blade pitch angle in several steps) close to the envelope of the c_p-λ-chart will be studied. This would result in a certain performance gain.

Wind Direction Misalignment

The yaw drive system will be actuated when the rotor axis is misaligned more than 5^o with respect to wind direction.

Due to this effect a small power loss is theoretically predicted.

The test program includes measurements of power output and rotor loading at different rotor misalignments.

Rotor Teetering

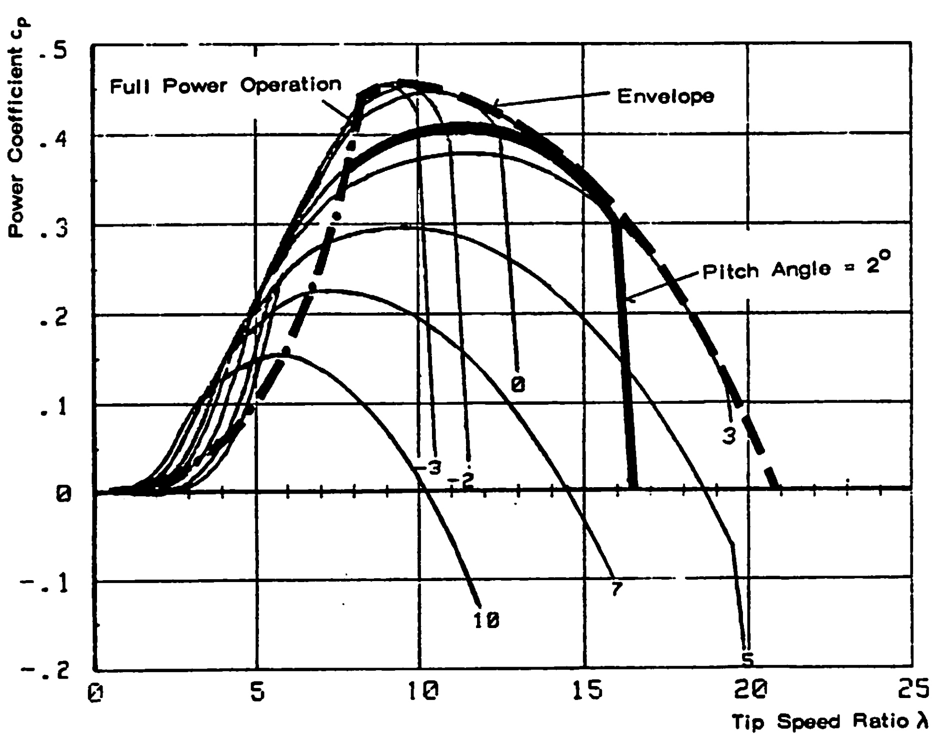
GROWIAN is designed and will be operated with a teetering rotor.

Nevertheless it is foreseen to block the pendulum hub and perform a test program with a fixed rotor. The results of theoretical calculations do not allow a definitive conclusion about the general advantage of a teetering rotor. For this reason an experimentally trade off investigation should be carried out.

Fig. 10 Power Control Procedure

Full Load : Blade pitch angle control according to max. allowable generator output and overspeed

Partial Load: Constant blade pitch angle ($\vartheta = 2°$)
or
pitch angle control close to the envelope of the Cp - λ - chart



Test Program

- Nominal operation at partial load with $\vartheta = 2°$ = const.
- Feasibility of control method close to Cp - λ - envelope (measurement of the performance improvement)

Fig. 11

Wind Direction Deviation

Start of the yaw drive system at 5° misalignment of the rotor axis with respect to the wind direction

Test Program

- Measurement of power losses and rotor loading at different rotor misalignments

Rotor Teetering

Teetering rotor coupled with cyclic blade pitch angle control

$$\frac{\text{teetering angle}}{\text{blade pitch angle}} = 1 : 3$$

Test Program

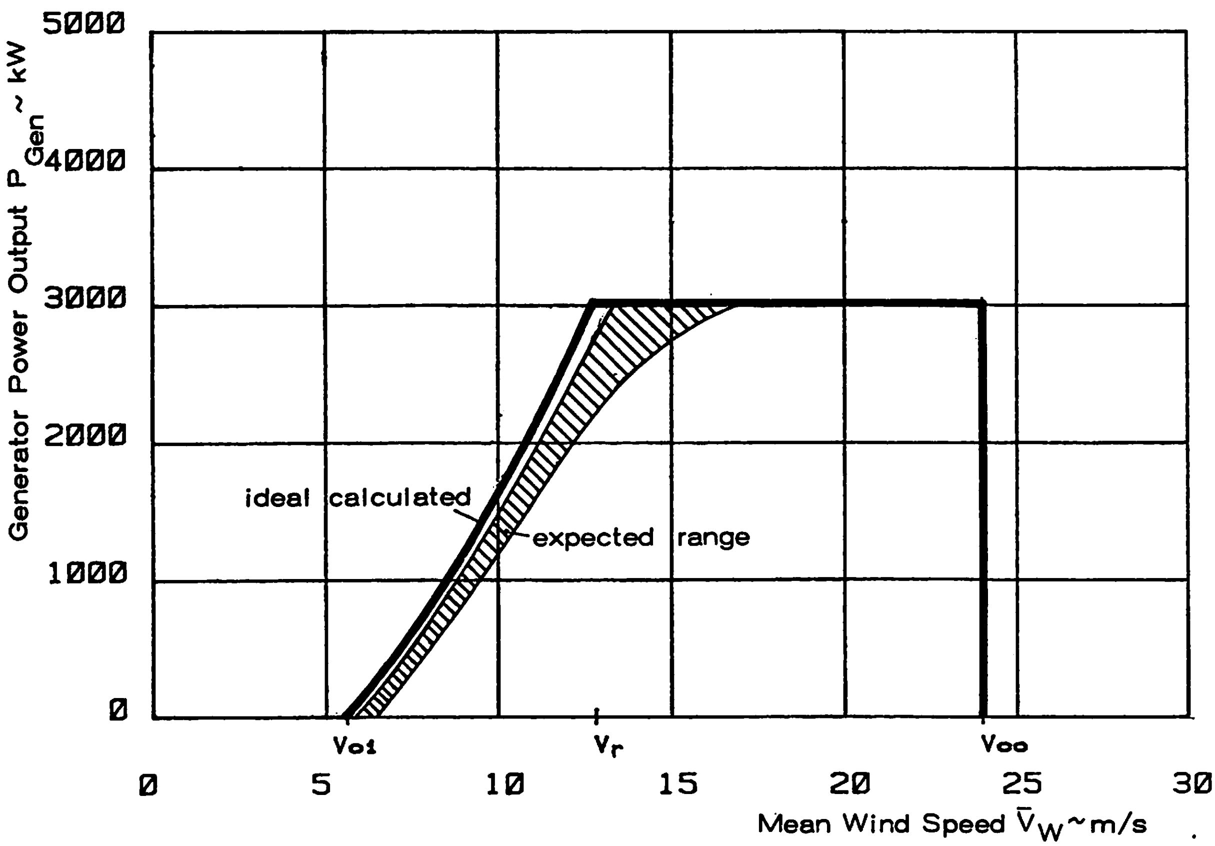
- Nominal operation with pendulum hub
- Test program with blocked hub, i.e. fixed rotor (requires additional hardware and modification of the hub)

IV. RANGE OF EXPECTED POWER OUTPUT

The power output calculations for a given wind rotor configuration can be performed with a good accuracy by means of the available theoretical models. Deviations from the results, which are based on ideal conditions, are caused by the real conditions discussed before. The power losses, due to such effects as tower shadow, surface roughness of the airfoils, rotor axis misalignment etc. can be calculated with more optimistic or more pessimistic assumptions. For this reason Figure 12 shows the calculated power output based on the idealized mathematical model and gives the range of expected output considering estimations for power losses.

The appropriate annual energy output has been calculated from 9.8 GWh based on pessimistic assumptions to 11 GWh with more optimistic figures.

Fig. 12 Range of Expected Power and Energy Output



Annual Energy Output at the Site

ideal calculated : 11.5 GWh

real expected : 9.8 to 11.0 GWh

DOE/NASA WIND TURBINE DATA SYSTEM

H. NEUSTADTER

R. WOLF

LEWIS RESEARCH CENTER

INTRODUCTION

BACKGROUND

ENVIRONMENT

FUNCTIONS

TRANSDUCERS

DATA FLOW

COMPONENTS

DIGITAL ANALYSIS

BACKGROUND

OBJECTIVES

- TO SUPPORT INSTALLATION AND DESIGN

APPLICATIONS

- ATTAINING OPERATIONAL READINESS
- DIAGNOSING MALFUNCTIONS
- ASSESSING PERFORMANCE

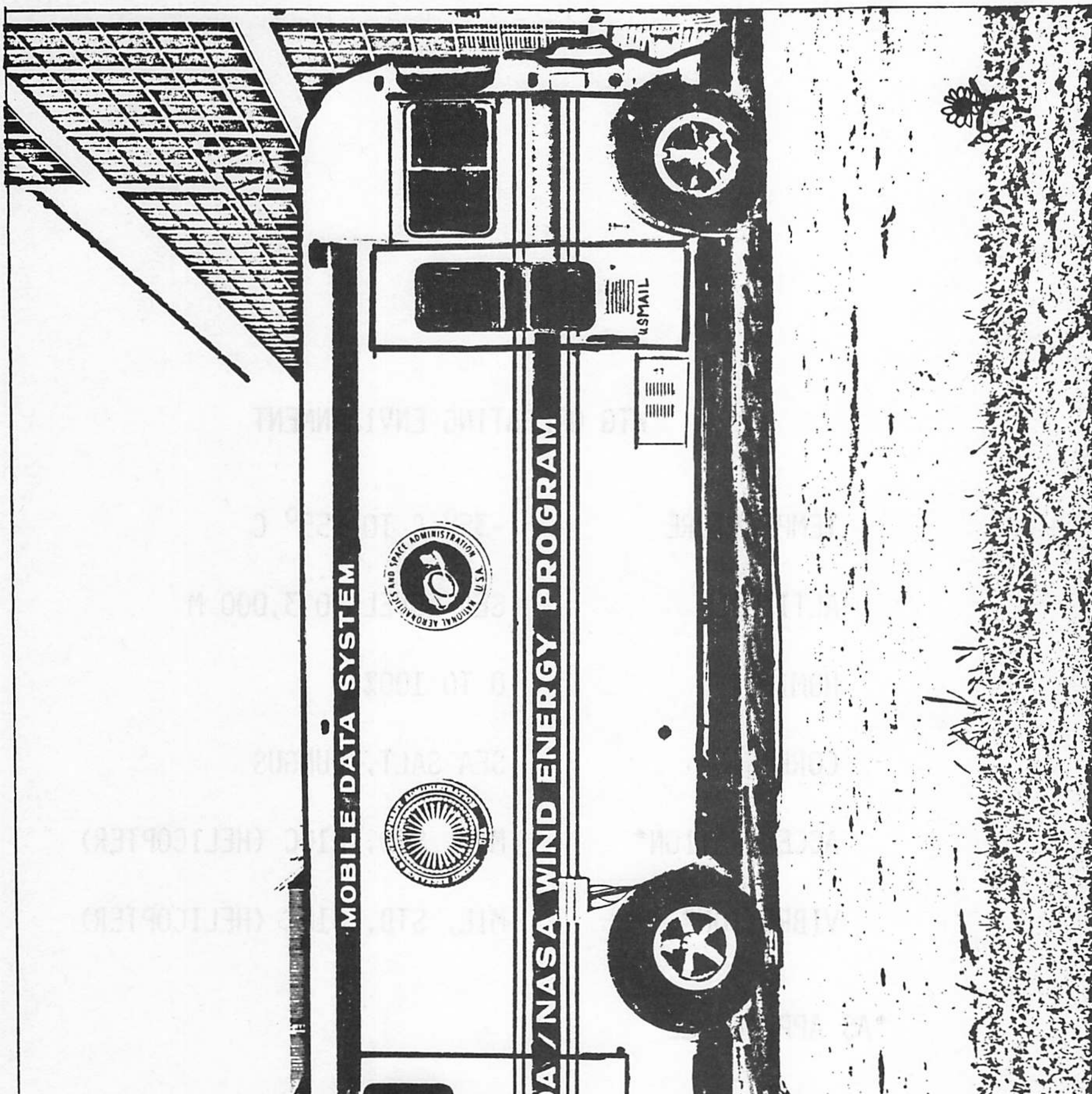
REQUIREMENTS

- ON LINE DISPLAYS OF ENGINEERING DATA
- COMPACT ARCHIVING OF ALL DATA
- REMOTE SITE OPERATION
- FULLY INTEGRATED SYSTEM

BACKGROUND (CON'T)

APPROACH

- FM TRANSMISSION
- FM RECORD
- COMPUTER CONTROL
- FULLY INTEGRATED SYSTEM
- HARDWARE DIGITAL COMPRESSION
- MOBILE SYSTEM


MOBILE DATA SYSTEM
ERDA / NASA WIND ENERGY PROGRAM
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
U.S.A.
U.S. MAIL

WTG OPERATING ENVIRONMENT

TEMPERATURE	-35^{o} C TO $+55^{o}$ C
ALTITUDE	SEA LEVEL TO 3,000 M
HUMIDITY	0 TO 100%
CORROSION	SEA SALT, FUNGUS
ACCELERATION*	MIL. STD. 810C (HELICOPTER)
VIBRATION*	MIL. STD. 810C (HELICOPTER)

*AS APPLICABLE

FUNCTIONS

TRANSDUCE
- STRAIN GAGE
- THERMOCOUPLE
- VOLTAGE OUTPUT
- CURRENT OUTPUT

CONDITION
- CONVERT TO FM
- MULTIPLEX
- TRANSMIT VIA COAXIAL CABLE

RECORD/PLAYBACK
- ALL DATA AS FM MULTIPLEX
- TIME

DISPLAY
- STRIP CHART
- CRT
- SPECTRUM ANALYZER
- PRINTER/PLOTTER

REDUCE
- COMPRESSED DIGITAL RECORD
- STATISTICAL ANALYSIS

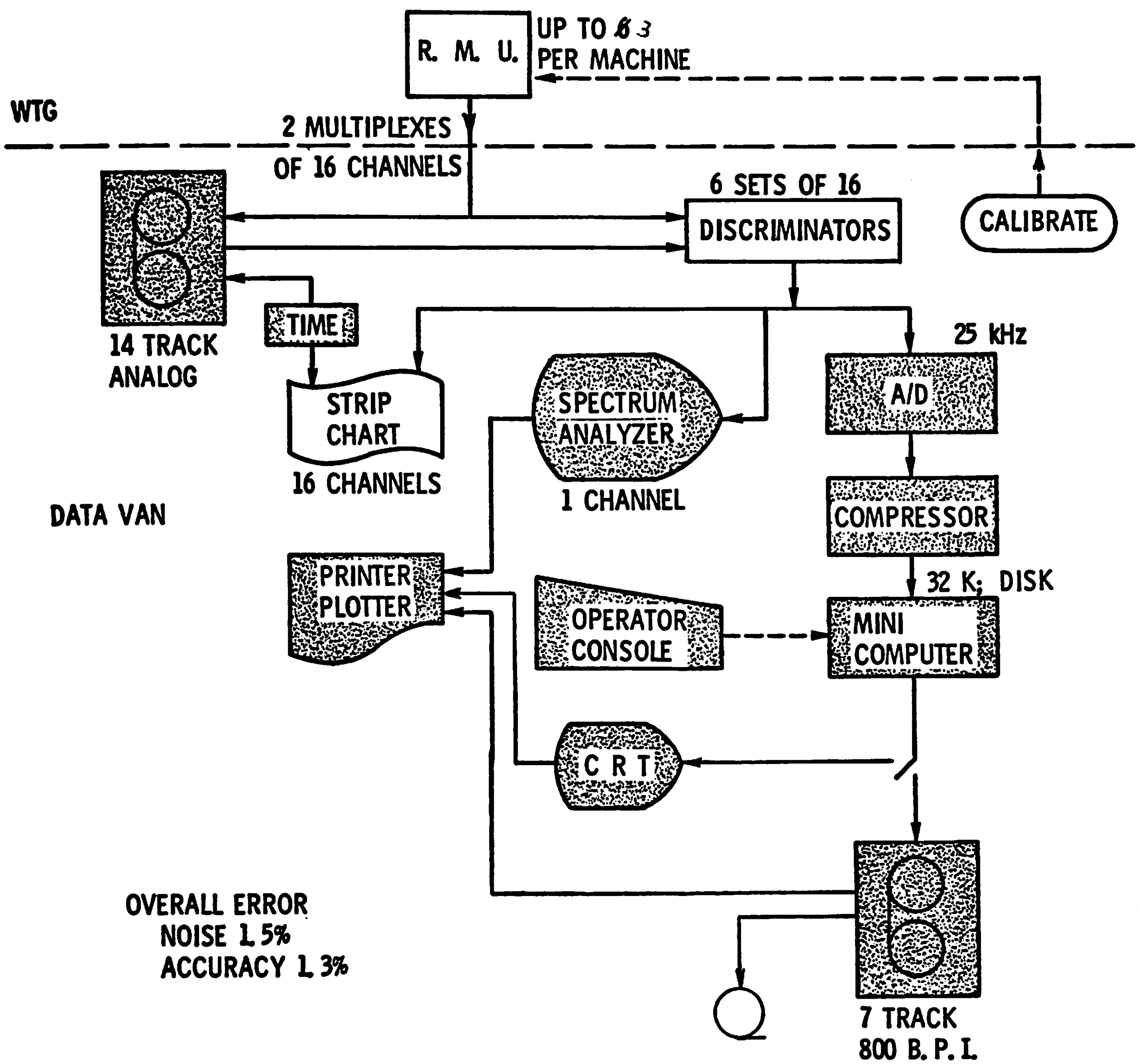
TRANSDUCER CALIBRATION

TRANSDUCER	CALIBRATION	CALIBRATION MAINTENANCE
STRAIN GAGE	APPLICATION OF KNOWN LOAD	GRAVITY CHECK
THERMOCOUPLE	REFERENCE TABLES/TEMPERATURE REFERENCE	ICE POINT CHECK
ACCELEROMETER	FACTORY	GRAVITY CHECK
ELECTRICAL	FACTORY	SENSOR CROSS CHECK
WIND	FACTORY (WIND TUNNEL)	PERIODIC REPLACEMENT/WIND TUNNEL CALIBRATION

TRANSDUCER FEATURES

MEASURED PARAMETER	TRANSDUCER TYPE	OPERATING PRINCIPLE	BANDWIDTH
STRAIN BENDING MOMENT	STRAIN GAGE BRIDGE	CHANGE IN RESISTANCE DUE TO CHANGE IN STRAIN	DC TO 40 HZ
TEMPERATURE	THERMOCOUPLE	BI-METAL JUNCTION	DC TO .1 HZ
ACCELERATION	ACCELEROMETER	SERVO/FORCE BALANCE	DC TO 10 HZ
POWER	WATTMETER	HALL EFFECT	DC TO 10 HZ
VOLTS	POTENTIAL TRANSFORMER		DC TO 10 HZ
CURRENT	CURRENT TRANSFORMER		DC TO 10 HZ
WIND	ANEMOMETER/WIND VANE	TACH GENERATOR/POTENTIOMETER	DC TO 10 HZ

DATA VAN OVERVIEW



COMPONENTS

REMOTE MULTIPLEX UNIT (R.M.U.)

- 32 CHANNELS PER UNIT (EXPANDABLE)
- DIVERSE TRANSDUCER INPUT
- 0-40 Hz CHANNEL BANDWIDTH
- FREQUENCY MODULATION; CENTER BAND ± 125 Hz
- 16 DATA CHANNELS PLUS REFERENCE PER MULTIPLEX
- OPERATE IN WIND TURBINE ENVIRONMENT
- NO EXTERNAL CONTROL REQUIRED
- 400 METERS TRANSMISSION (EXTENDABLE)
- ACCEPT CALIBRATE COMMANDS

COMPONENTS (CON'T)

FM RECORD/PLAYBACK UNIT

- TIME CODE + FM MULTIPLEXES
- DIRECT RECORD, WIDEBAND I
  - 1-7/8 I.P.S.
  - 0.4 TO 25.0 kHz
  - S/N: 25 dB
- 14 TRACKS
- 15 INCH REEL; 1 INCH TAPE

TIME CODE

- GENERATE/TRANSLATE
- IRIG B (DAY, HR., MIN., SEC., mSEC)

COMPONENTS (CON'T)

FREQUENCY DISCRIMINATORS

- MATCHED TO LOWER 8 RMU FREQUENCIES
- DETRANSLATION OF UPPER 8 FREQUENCIES
- 0 TO 40 Hz
- ANALOG OUTPUT, ± 10 V
- TAPE SPEED COMPENSATION

COMPONENTS (CON'T)

ANALOG/DIGITAL MULTIPLEXER

- UP TO 128 CHANNELS
- UP TO 100,000 SAMPLES/SECOND
- 12 BIT RESOLUTION (1/4000)

DATA COMPRESSION UNIT

- 128 CHANNELS
- SEPARATE ALGORITHM FOR EACH CHANNEL

  REJECT/PASS

  BIT MATCH/NO BIT MATCH

  IN LIMITS/OUT OF LIMITS

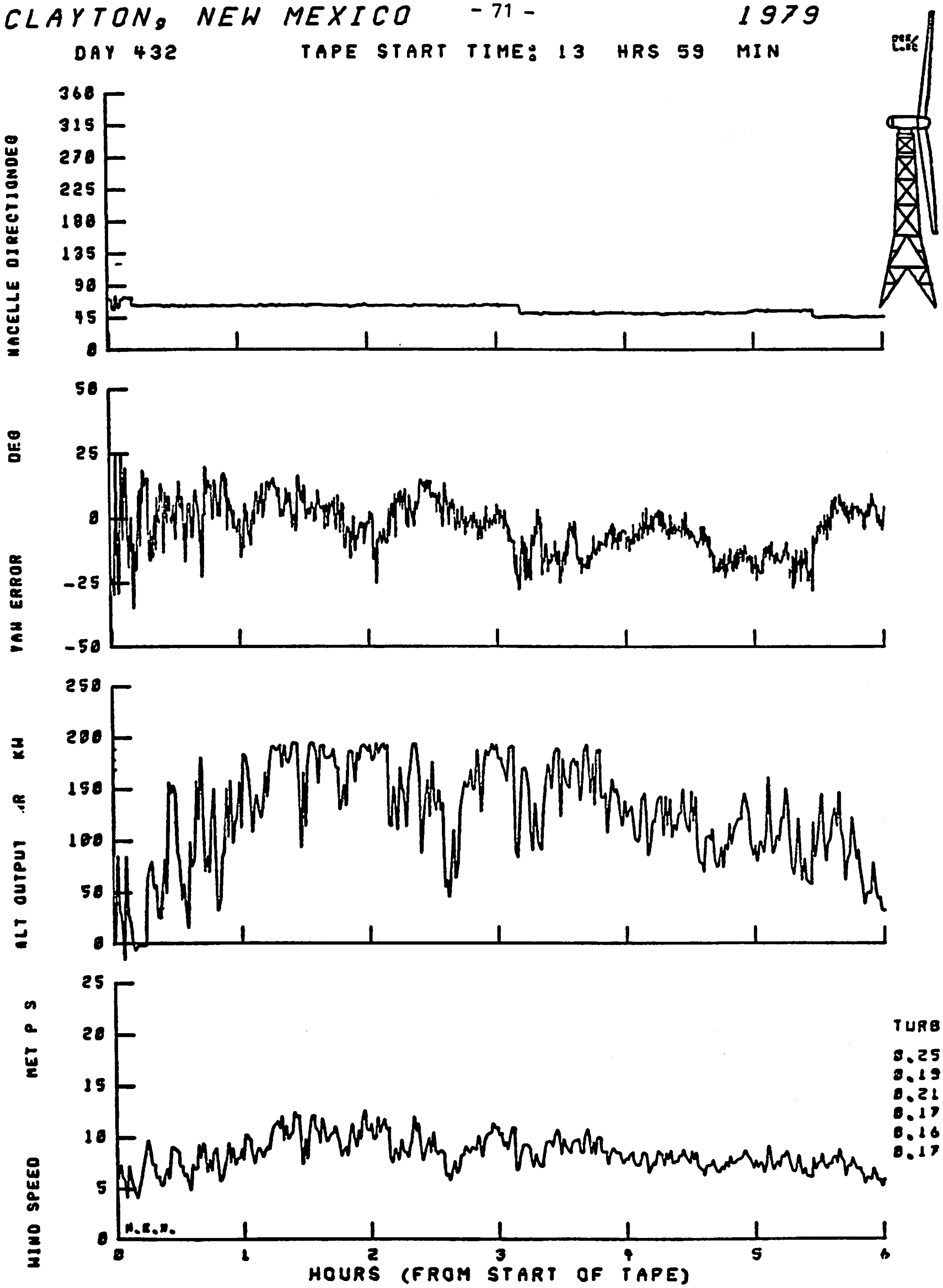
  BIT CHANGE

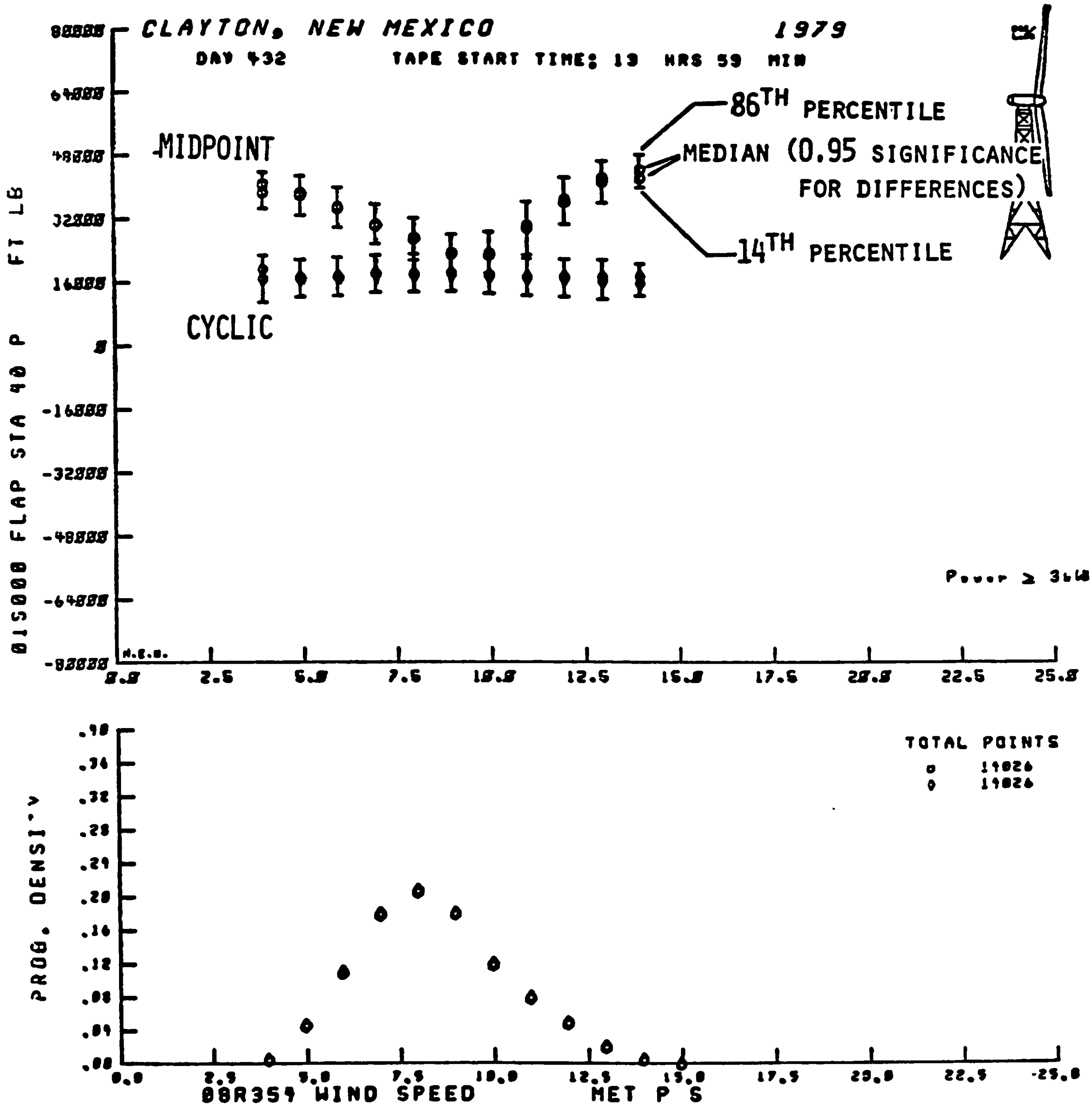
  AMPLITUDE CHANGE BY PERCENT

  PASS EVERY N^{TH}

CLAYTON, NEW MEXICO 1979

DAY 432 TAPE START TIME: 13 HRS 59 MIN




CLAYTON, NEW MEXICO 1979
DAY 432 TAPE START TIME: 13 HRS 59 MIN
MIDPOINT
CYCLIC
86TH PERCENTILE
MEDIAN (0.95 SIGNIFICANCE FOR DIFFERENCES)
14TH PERCENTILE
FT LB
Power ≥ 3kW
TOTAL POINTS
14026
14026
PROB. DENSITY
WIND SPEED MET P S

SUMMARY

- MATCHED, INTEGRATED SYSTEM
- SUPPORTS WTG INSTALLATION AND INITIAL OPERATION
- PROVIDES DATA FOR DESIGN ENGINEERS

1979-09-18
P-Å Johansson/IE

EVALUATION OF THE PROTOTYPE PROJECT OF THE SWEDISH WIND ENERGY PROGRAMME

INTRODUCTION

The prototype project is the major part of the Swedish wind energy programme. Teh programme is conducted by the Swedish Board for Energy Source Development, in Swedish abbreviated NE.

The project comprises concept studies followed by design, erection and evaluation of two larg scale horizontal axis WECS.

Together with other projects in the wind energy programme, the purpose of this project is to provide basic information for a possible decision in the direction of large scale utilization of wind energy in Sweden. This decision is scheduled to be made around 1985. The project has now reached the implementation phase.

Early this summer NE came to agreements with two prototype contractors, Karlskronavarvet AB (Kkrv), part of the Swedish state shipyard group, and Karlstads Mekaniska Werkstad AB (KMW), part of the Johnson group. Both agreements hav later been confirmed by the Swedish government.

The prototypes

The main characteristics of the units are listed in table 1 below, together with the corresponding requirements stated in the request for proposals.

Table 1. Prototype main characteristics

	Kkrv	KMW	RFP
Rated power (MW)	3.0	2.0	2-4
Turbine diameter (m)	77.6	75.0	70-90
Number of blades	2	2	2-3
Blade type	GRP	Steel+ GRP	Optional
Tip speed (m/s)	101.5	98.1	≤170
Turbine orientation	Downwind	Upwind	Optional
Hub height (m)	80	80	≥Turbine dia.
Hub type	Teetered	Rigid	Optional
Generator type	Synchr/ /1 500 rpm	Induction/ /1 500 rpm	Optional
Tower design	Steel shell	Concrete	Optional

cont. Table 1

	Kkrv	KMW	RFP
Rated Wind speed (m/s)	14.2	12.5	Optional
Cut in wind speed (m/s)	6	6	6
Cut out " " (m/s)	21	21	≥21
Blade pitch control	Computer + hydraulic	Computer+ hydraulic	Required
Yearly energy production[1] (GWh)	8.1	6.7	-

[1] Hypothetical wind conditions equal for both prototypes but not equal to conditions on the prototype sites

Siting and operation

Sites for the prototypes are shown in figure 1. The Kkrv prototype will be erected near the south coast in the province of Skåne in southern Sweden while the KMW unit will be sited on the island of Gotland. The sites have favourable wind conditions. The yearly median winds being approx. 9 m/s on both sites. From an evaluation point of view and also considering operation and maintenance the selected sites are less favourable, particularly the site on Gotland. The units will be connected to the national Swedish power grid at 50 kV and 30 kV voltage levels. The available short circuit power at the connection points would be 150-800 MVA according to the RFP specification, but will be as low as 50 MVA for the Gotland site.

The day to day operation and the maintenance of the units will be assigned to Sydsvenska Kraft AB and to the Swedish State Power Board, the utilities which are operating in the areas where the units are located.

Time schedule

The different phases of the implementation of the two units are planned to run roughly according to identical time schedules.
An overall time schedule for remaining activities of the prototype project is shown in figure 2.

Evaluation

In figure 2 are also indicated the evaluation activities to be conducted during the remaining phases of the project. These activities are planned to be carried out in a systematic and well documented manner.

- Studies and evaluation of the implementation

  During final design of the units and subsequent manufacturing and installation NE will closely supervise technical and economical aspects of the delivery. From the technical point of view, new technology and "old technology" in new applications will be of major interest together with problems associated with transportation of large components to the site an also erection.
  The aim of the economical studies is to obtain a base for more accurate cost estimates of WECS manufactured in larger series.
  Planning of the evaluation activities during this phase has recently been started.

- Delivery test

  The delivery tests shall verify that

  o Functional requirements on the unit and its subsystem are met.

  o Loads and stresses at critical points do not exceed the design limits.

  o The unit is capable of producing energy according to the specification.

  o Other contractual requirements are fulfilled.

  The main part of the delivery tests will be performed during the test period indicated in figure 2. If wind conditions are unfavourable, some test may be postponed to a later date.

  The testprocedures for the delivery test will be worked out by the contractor. NE has however the right to influence them. The contractor will also carry out the testing with NE having contractual rights of full supervision of the tests.

- Studies of the operational units

  The evaluation work to be performed during this phase will be conducted by NE, but executed with external assistance from among others the utilities operating the units and the prototype contractors.

Activities to be performed during this phase are:

- o Acquisition and evaluation of engineering and operational data, utilizing qualified data aquisition systems.
- o Logging of experiences from operation and maintenance of the units. Techical and economical.
- o Studies of the unit´s influence on the environment.
- o Studies of costs for operation and maintenance.

Planning of activities during this phase will be started later this fall.

A preliminary listing of the studies to be performal has, however, already been made as a basis for specification of the data acquisition systems for the prototypes.

MEASUREMENTS AND STUDIES ON THE PROTOTYPE SITES

Measurements on the prototype sites during delivery tests and the subsequent test period will be performed utilizing one permanently installed data acquisition system, DAS, in each prototype.
Originally the data acquisition systems were intended to be part of the delivieries of the prototypes and included in the procurement of the units. On a late stage, shortly after the prototype proposals had been recieved there was a decision made, that the DAS should be separately specified and procured.
There were several reasons for this decision.
The RFP had on this point been interpreted in widely different ways. Each bidder had his own ideas about level of qualification and the scope of delivery for the DAS.

As a result there would be a risk of not being able to perform equivalent evaluation of the two units.

Secondly it was judged that NE´s ambition to be essentially independent of the prototype contractors in its evaluation work would be difficult to maintain with the systems proposed. Generally, the measurement facilities were closely tied to the control systems of the units.

Further, the ideas about the requirements on the evaluation were at this stage a bit unspecific, not exactly suited for a final decision on the capabilities of the DA

A committee was formed and was given the task to prepare a separate procurement of the data acquisition systems. The idea was to make one specification for the complete DAS i. e. instrumentation (primary sensors, signal conditioning and transmission) and data recording equipment. Realizing that the instrumentation was an integral part of the prototype and if possible should be included in the prototype contract we changed opinion in order to prepare the instrumentation specification in time for coordination with the prototype procurement. It would be possible to specify the data registration equipment, i. e. computer systems, later if special attention was paid to the interface between instrumentation and computer system in the specification work.

For the work the following general requirements were set up:

- Both prototypes should be equipped with identical systems as far as differences in prototype design allowed.

- The data acquisition systems should in principle be separated from the control system of the units.

- The system should within reasonable limits be "complete", i. e. meet the needs for data registration of various types and for various purposes. Measurement tasks which are best solved with temporary installations should not be taken into account.

In its work, the committee has been assisted by external experts:

- Meteorologists from the university of Upsala and from the Swedish Meteorological and Hydrological Institute, SMHI.
- Representatives from the utilities which will be responsible for the operation of the units.

- Experts on electrical matters from the Institutes of Technology in Lund and Gothenburg (Chalmers).

- The potential prototype contractors.

The committee itself represents experience in aerodynamics and structural dynamics and also experiences from the evaluation of the Swedish 60-kW experimental unit. Consequently the conditions for obtaining a complete coverage of the various evaluation aspects must be considered to have been good.

The first result of the committee's work was a document named "Tasks and Goals of Prototype Evaluation". It gives a listing and rough description of the studies to be performed on the prototype sites and was compiled to give a basis for the specification of the instrumentation and data acquisition computer systems.

It contains the following main sections:

1. General
2. Evaluation of the WTS as a power plant
3. Loads and stresses
4. Fault monitoring
5. Environmental effects
6. Other evaluation tasks
7. List of measurands

I will comment on the major points of interest in each of these sections and will also, where relevant, comment on specific methods which are suggested for the evaluation.

General

This section describes the purpose of the document. A short description is given of the meteorological system which will be installed on each prototype site. These systems are installed and operated by SMHI, under contract with NE. The systems will be interfaced to the prototype DAS:s.

Evaluation of the WTS as a power plant

This section deals with plant power and energy procuction and consumption, the plant's interaction with the power grid and the availability of the plant.

The power output as a function of wind velocity will be determinded as a routine measure. It will, however, not be relied upon as a verification of the prototype design. The reason for this is the obvious problems of obtaining a good measure of the undisturbed velocity of the wind passing through the rotor disc area.

For verification of the performance of the prototype an entirely different method will be used. This method is agreed upon by the prototype contractors and NE. The wind speed duration curve for a specific period of time will be determined. This duration curve will be combined with the precalculated wind power curve of the unit (design data), yielding a theoretical energy output under given wind conditions. The calculated energy output will be compared with the real-measured-energy output from the same period of time.

A number of specified conditions shall be fulfilled among them:

- All wind speeds within the operating range of the unit shall have been prevailing during a minimum time of the test period.
- The theoretical wind speed vs. power curve shall be adjusted with respect to actual cut in and cut out speeds as well as rated power, if they differ from the theoretical values.
- The wind speed shall be determined using wind measurements from the meteorological system. The measurements will be made in a specified manner. Wind speeds on three levels shall be weighed to give a good representation of the average wind speed over the disc area. The time average of the wind speed shall be calculated in a specified manner.

Energy production and associated wind conditions will be recorded essentially during the entire evaluation period. Then data will be used in studies of system balance. As a necessary complement to the energy production data from the prototypes will serve wind speed data from 12 different locations in Sweden. Under a separate NE project conducted by SMHI, existing masts will be equipped with aremometers up to 100 m height.

Power losses and internal energy consumption of the units will be studied.

Energy consumption of auxiliary systems such as hydraulic system, heating and control system will be measured with energy meters.

Losses in energy production caused by misalignment of the axis of rotation of the turbine in relation to the wind direction has been discussed during the evaluation of the prototype tenders. An investigation requires reliable measurements of mean wind direction over the disc area which seem as difficult to obtain as reliable wind speed data.

The behaviour of output voltage and power at transient conditions such as wind gusts and connection and disconnection of the generator will be studied.

The availability of the units will be studied using automatic data acquisition as far as possible.
The aim is to obtain, essentially for the entire evaluation period, a complete survey of

- the time of operation of the unit.
- the time of standstill of the unit for various reasons: lack of wind, technical faults and preventive maintenance.

By combining wind data and information on the unit´s mode of operation, energy "losses" caused by standstill during windy conditions can be calculated.

Automatically collected data will have to be supplemented by manually logged information about fault reasons, time for repair and maintenance etc. to make the availability study complete.

Loads and stresses

This section describes measurements of extreme loads fatigue loads and vibrations.

In these measurements it is necessary to use elaborate methods to extract relevant data from very large amounts of raw data. Methods which are so far discussed are:

- Measurements are limited to selected periods of time with specific wind conditions or operating conditions such as start up, shut down, overspeed of the turbine.
- Extreme loads or generally extreme operating conditions may be captured using limit supervision and/or a flight recorder function. The flight recorder function or past history log will make it possible to study time recordings of analogue measurands around significant events. The recordings will include limited time intervals before and after the event. Intervals of 30 minutes before an event has been mentioned to be of interest by one prototype supplier.
- Direct and continuous recording of load spectra. One method of determining load spectrum named "range pair exceedance count" is suggested by the Swedish Structural Welding Code issued by the National Swedish Committee on Reulations for Steel Structures.

This methos has been used off line in the evaluation of the Swedish test unit in Kalkugnen. At the end of this year an on line version will be implemented on the DAS of the test unit. The method is explained in figure 3.
Local maxima on the strain gauge signal (or computed load) are identified. The range of one possitive and one negative maximum is compared with a number of predetermined amplitude levels, say 20-40 levels. Each match results in a "count". When evaluating, the number of counts are plotted in a count versus strain level diagram according to figure 4. The figure shows an example from the evaluation of Kalkugnen.

Recording of load spectra will be made for long periods of time. It will be desirable to make detailed studies of spectra during different wind and operating conditions. Storing of the level counts will therefore be made on a rather short time basis (a few minutes) possibly also dependant on wind and operating conditions.

Fault monitoring

Here we have a functional interface to the control systems of the units. The DAS:s are intended to give possibilities to study sequences of events at technical faults and extreme operating conditions in a better way than will be possible using the fault monitoring functions of the control systems.
Event logging will be implemented on both the control systems and the DAS:s, while on the DAS:s also the flight recorder function will be utilized for fault monitoring.

Environmental effects

Emission of audible noise and infra noise will be measured in the nacelle as well as outside the unit. Figure 5 illustrates the measurement set up used in Kalkugnen. At steady wind conditions, registration of sound pressure has been made four directions from the unit and at various distances. Measurements at the prototypes will be made in a similar manner.

TV interference

In the neighbourhood of the units disturbance of reception of TV transmissions are likely to occur. Transmissions in the UHF band are particularly sensitive to influence from the units.

Based on studies and measurements made in Kalkugnen the extention of disturbed areas around the prototypes have been predicted. Figure 6.
The validity of the predictions will be cheched by measurements.

Influence of the units on bird life will be observed.

Other evaluation tasks

This section is a "rest list" containing some general ideas such as

- Studies of different pitch control strategies

- Studies of ice build up on the blades.

List of measureands

For evaluation tasks based on data recordings by the prototype DAS, a list of measurands was compiled. In the list each measurand is named and requirements which are important for dimensioning of the instrmentation and the data recording equipment are given.

INSTRUMENTATION

The next step in the committee's work was to prepare a procurement specification of the instrumentation part of the data acquisition system. The specification was completed in time to be presented to the prototype suppliers before the prototype aggreements were signed and is now part of the agreement. The specification includes sensors, signal conditioning, signal transmission and an interface to the data recording equipment. Also included is auxiliary equipment for the recording equipment, rooming, power supply, ventilation etc, which is a natural part of the prototype delivery.
The requirements of the specification are functional. Within the requirements stated the supplier shall make a detailed design, which - according to the agreement - is negotiable and may be influenced by NE.

As a consequence of this "functional" approach, NE:s ambition to have identical systems on the two prototypes may not necessarily be fulfilled in detail. The number and type of measurands as well as the quality of the measurements will, however, definitely be compatible. Both contractors are interested in cooperating with each other and NE when designing the systems. Therefore it seems as though the systems will be made very similar in design, with the differences mainly caused by differences in design of the prototypes themselves.

The main sections of the specification are

- General
- Technical specification
- Scope of delivery.

Section General describes the scope of the specification, the purpose of the DAS and the relation of the DAS to the prototype subsystems.
It is stated that the DAS shall be, in principle, functionally independent of the control system of the prototype and vice versa.
Physical connections will occur. Some sensors of the control system will be used for measuring as well, and the control system computer will transfer information to the DAS.

Technical specification

Here the functional requirements of the system are specified. The technical quality of the delivery, installation requirements, methods for marking and labelling of the equipment are specified.
Requirements on the measurands of the system are given with references to the "list of measurands" mentioned above. For each measurand the following is - or will be - specified (see appendix 1):

Mätstorhet: Designation of the measurands. The type of the measurand is specified, the number of sensors is stated separately. A specific measurand may be specified several times to separate between different evaluation purposes, recording intervals, required frequency contents of the signal for different evaluation purposes and to allow separate indication that the measurand shall be utilized by the flight recorder function.

	Utvärderings-uppgift:	Reference to the document "Tasks and Goals . . .".
	Mätperiod:	Recording interval. Defines the extent of the interval. "Kont." means continuous recordings over the period of evaluation or at least very long recording intervals. If shorter intervals are stated, normally a few minutes, this indicates that each recording will be approximately that long. This information is used to estimate requirements on the recording equipment.
Mätkrav	Mätn./s.:	Number of samples per second. Is specified as an alternative to
	Frekvens-innehåll:	Frequency contents of the measured variable. A typical value is 0-20 Hz, which apply for strain measurements. For a few electrical parameters 0-200 Hz is specified.
	Mätnoggrannhet:	Permissible system inaccuracy measured at the interface to the recording equipment. In the specification text general requirements are stated: Strains and accelerations 4% Other measurands 2% Exceptions from these rules are stated in this column.
	Fellogg:	A mark in this column indicates that the measurand will be utilized by the flight recorder function.
Givare	Placering mätpunkt:	Location of sensor.
	Typ/fabrikat:	Type/make of the sensor.
	Antal (exkl. redundans):	Number of sensors (not including redundant sensors).

Redundans: Redundancy. A mark in this column indicates that each sensor shall have a back up sensor. A general statement of the specification text says that "sensors which are impossible or diffecult to repair or replace shall be duplicated". Redundant sensors shall be equipped with cabling to an easily accessible connection point.

Övr. givarkrav: Other requirements on the measurand in question.

Beräkningar

On line: Calculations to be made on line by the recording equipment are mentioned here.

Utvärdering Calculations to be made when evaluating the recorded data are mentioned here.

Datalagring

Rådata: A mark in this column indicates that raw data will be recorded.

Beräknade: A mark inthis column indiates that the results of on-line calculations will be recorded

Anm: Remarks.

In table 2 the total number of sensors per prototype "sub system" are listed. The figures of table 2 are not obtained by simply summering up the figures of the column "number of sensors".
Included in the list of measurand and table 2 are signals from the meteorological system. These signals will be interfaced to the DAS but the metorological instrumentation is not part of the prototype instrumentation.

Table 2. Number of sensors per sub system.

SUB SYSTEM	Analogue measurands	Indications	Pulse measurands
METOROLOGICAL SYSTEM	32	1	-
TURBINE & PRIMARY SHAFT	77	-	-
SEC.SHAFT & TORQUE LIMITER	2	-	-
NACELLE	27	1	-
TOWER	28	-	-
GENERATOR	13	-	2
GRID CONNECTION & AUXILIARY SYSTEMS	3	-	7
WTS CONTROL SYSTEM	5	45	-
Σ	187	47	9

The number of sensors is of course a preliminary contracted number, which will be altered during the final design of the instrumentation.

Computer interface

All measurands will be made available to the data recording equipment on a connection board - in the specification named computer interface - located in the WTS control room, where also the recording equipment will be installed.
The computer interface will have three main parts containing signals from respectively

- sensors on the prototype
- the control system of the prototype
- the meteorological system.

For each of these three sub systems two alternative interfaces are specified, a serial digital interface and a parallel analogue and digital interface. The alternatives are listed in table 4.

Table 4

"Sub system"	Serial	Parallel An signals	Di signals
WTS	"PCM interface"	0-10 V	Relay contact
Control system	CCITT V24	0-10 V	- " - -"-
Met system	CCITT V24	0- 4 V	- " - -"-

The "PCM interface" is the output of a PCM data transmission system. Data are made available in a word serial bit parallel mode.

Since the number of signals and long transmission distances are factors that call for multiplexed digital signal transmission the "parallel" alternative has been specified to serve as an "emergency exit" to be utilized if serial interfaces of the instrumentation and the data recording equipment can not be matched in a satisfactory manner.
For the time being we have good hope to be able to avoid the "emergency exit". Both prototype suppliers are interested in using the same type of data transmission equipment, which in turn is comparatively easy to interface to any computer. For the CCITT V24 interfaces it will probably be no problem to define suitable protocols.

Signal transmission

Both suppliers will utilize digital serial transmission of signals between sensors/signal conditioning equipment and the computer interface. The specification allows this type as well as parallel transmission on individual conductors.

Some type of telemetry will probably be used for transmission of signals between turbine - nacelle - tower. Transmission on slip-rings, which is specified as an option, was initially discussed with the suppliers. Recently, however, a 200 MHz radio link has been suggested by one contractor. Signals from the turbine will be transmitted to the nacelle and joined here by nacelle signals. All signals are then transferred to the tower on a similar radio link.

Test outlets

All signals from the WTS are specified to be available on test outlets, which shall be located in the vicinity of the primary sensors. The test outlets are intended for calibration and maintenance purposes.
Since serial signal transmission will be utilized, a practical solution for test outlets is to arrange connection points for a mobile test box on a few selected locations along the transmission line. The test boxes will have a limited number of outlets, but be programmable so that any measurand can be connected to any outlet.

Scope of delivery

In this section is listed the work to be carried out by the contractor regarding:

- Design and manufacturing
- Installation
- Testing
- Documentation.

DATA RECORDING EQUIPMENT

Computer based systems are obviously a necessity if it shall be possible to implement some of the recording methods mentioned previously. To allow NE to decide on a suitable level of ambition of the system, i.e. what is economically and technically feasible and necessary, a prestudy has been made identifying different ambition levels and associated price tags.
A preliminary decision has been made to specify and purchase two systems with the following main features.

- The data acquisition shall be controlled by the system itself to a great extent to allow unattended operation and facilitate attended operation of the system.

- Data from long term measurements shall be reduced before recording; raw data shall be recorded when short term measurements are made.

- Final processing of recorded data shall be made off-site. Facilities for a preliminary check of recorded data on site shall, however, be provided.

- To ensure a high quality of the data recorded, facilities for adequate book-keeping of recordings and system check functions will be provided.

- The system shall be relatively easy to operate for personell without knowledge of computer programming.

- Modifications and additions of system functions shall be relatively easy to carry out.

The specification is under way. RFP:s are planned to be sent out in November. The aim is to have a turnkey delivery from one of the, say 3, companies in Sweden which are capable of supplying systems of this kind. Several of the system functions which are related to wind energy will be undefined at the time of purchase. Efforts will be made to identify and include in the purchase system functions which have major influence on the system design.

A preliminary hardware configuration of the system being specified is shown in figure 8.

System functions can only be schematically described.

Data acquisition

All sensors/signal sources will be permanently connected to the system. Signals to be recorded are selected by program control. Measurements are made in three modes

- continuous measurements. Recorded continuously are mainly power production and consumption data, meteorological data and fatigue load data.
- campaign measurements. All measurands will be recorded in suitable combinations. Recording periods are a few seconds up to an hour depending on time resolution of the recording.
- past history log. Parameter combinations and recording periods as for compaign measurements.

Data reduction

Will be performed on continuously measured data as an on-line calculation. Typical calculations are time averaging of wind and power data and fatigue load calculations.

Storing of data

Data acquired in all measurement modes will be temporarily stored on disc storage. From here data are available for on site check and evaluation.
Magnetic tape will be used as a "final" storage and will be the interface to the computer on which final processing is made.
Continuously measured data will be transferred to tape from disc regularly, say once a day. Data from short term measurements will be transferred on operator´s request or automatically in case the system operates unattended.
Separate tape drives are foreseen for continuous and short term measurements.

On site evaluation

System functions for on site evalutation are intended for immediate check of recorded data when campaign measurement are performed with personell on site, for example during commissioning and delivery test of the WTS.
Functions to be implemented are

- Display of recorded data in analogue and alphanumeric modes on CRT and plotter/hard copy unit.
- Event recording of digital data.
- Mathematical and statistical caloulations. The results of the calculations will be available in graphical and alphanumeric form on display and in hard copies.

System control

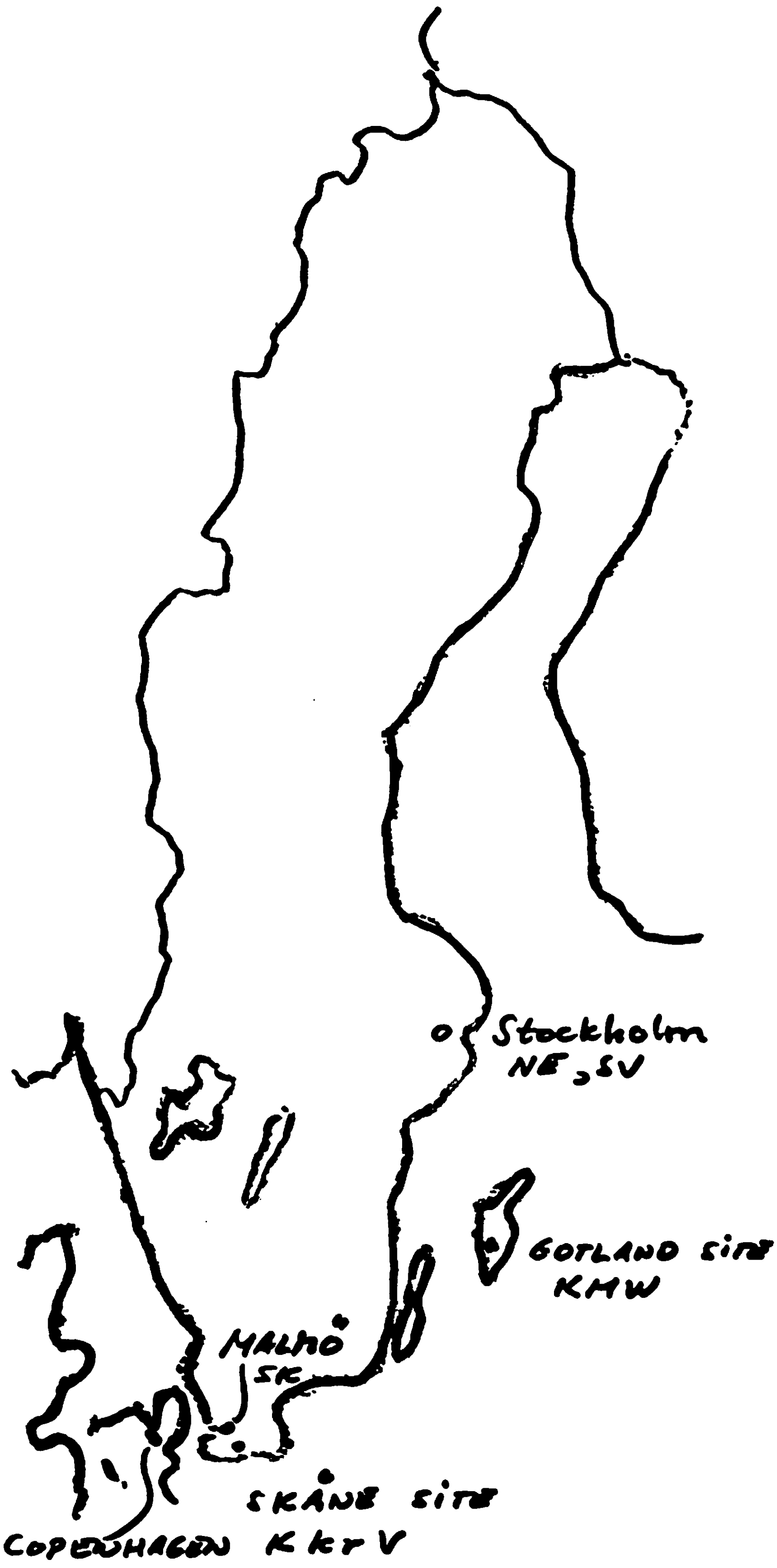
Facilities for set up and change of parameter combinations, scale factors, recording period etc. for all measurement modes will be provided. The set-up will be made via a CRT-display in a man-computer dialogue. Parameters etc. defined will be stored together with measured data.

Recordings will be initiated/stopped either by operator commands or automatically by the system.
A number of different parameter combinations for campaigns and past history recordings may be preselected. Recordings may then be triggered by the system itself when conditions specific for each combination are fulfilled.
Conditions may be

- the WTS is in a specific mode of operation, e.g. start up, emergency stopping, turbine overspeed.
- specific wind conditions prevail.
- measured variables exceed preset limits.

Time controlled data acquisition may possibly be used to reduce data volumes from continuous measurements. It may be sufficient to record wind conditions, production data and load spectra intermittently, say during a few minutes each hour and still obtain significant results.

FIG. 1


Stockholm
NE, SV
GOTLAND SITE
KMW
MALMÖ
SK
SKÅNE SITE
COPENHAGEN KKrV

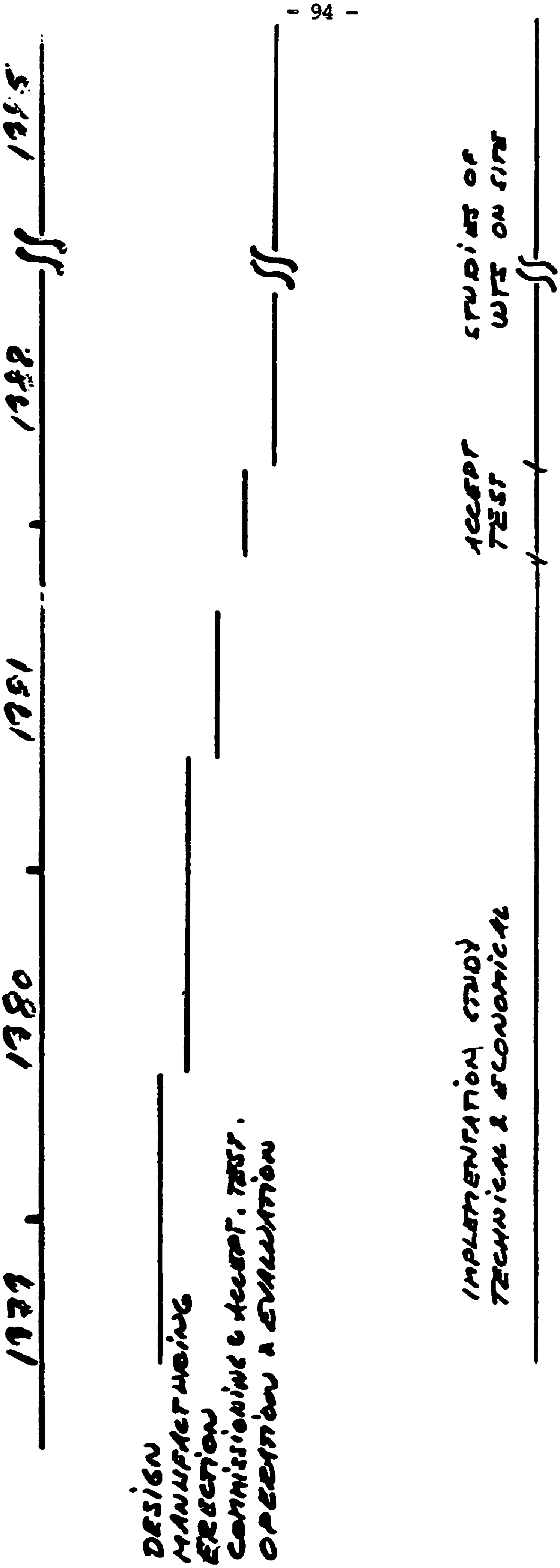

1979
1980
1981
1982
1985
DESIGN
MANUFACTURING
ERECTION
COMMISSIONING & ACCEPT. TEST.
OPERATION & EVALUATION
IMPLEMENTATION STUDY
TECHNICAL & ECONOMICAL
ACCEPT TEST
STUDIES OF WTS ON SITE

FIG 2.

FiG. 3

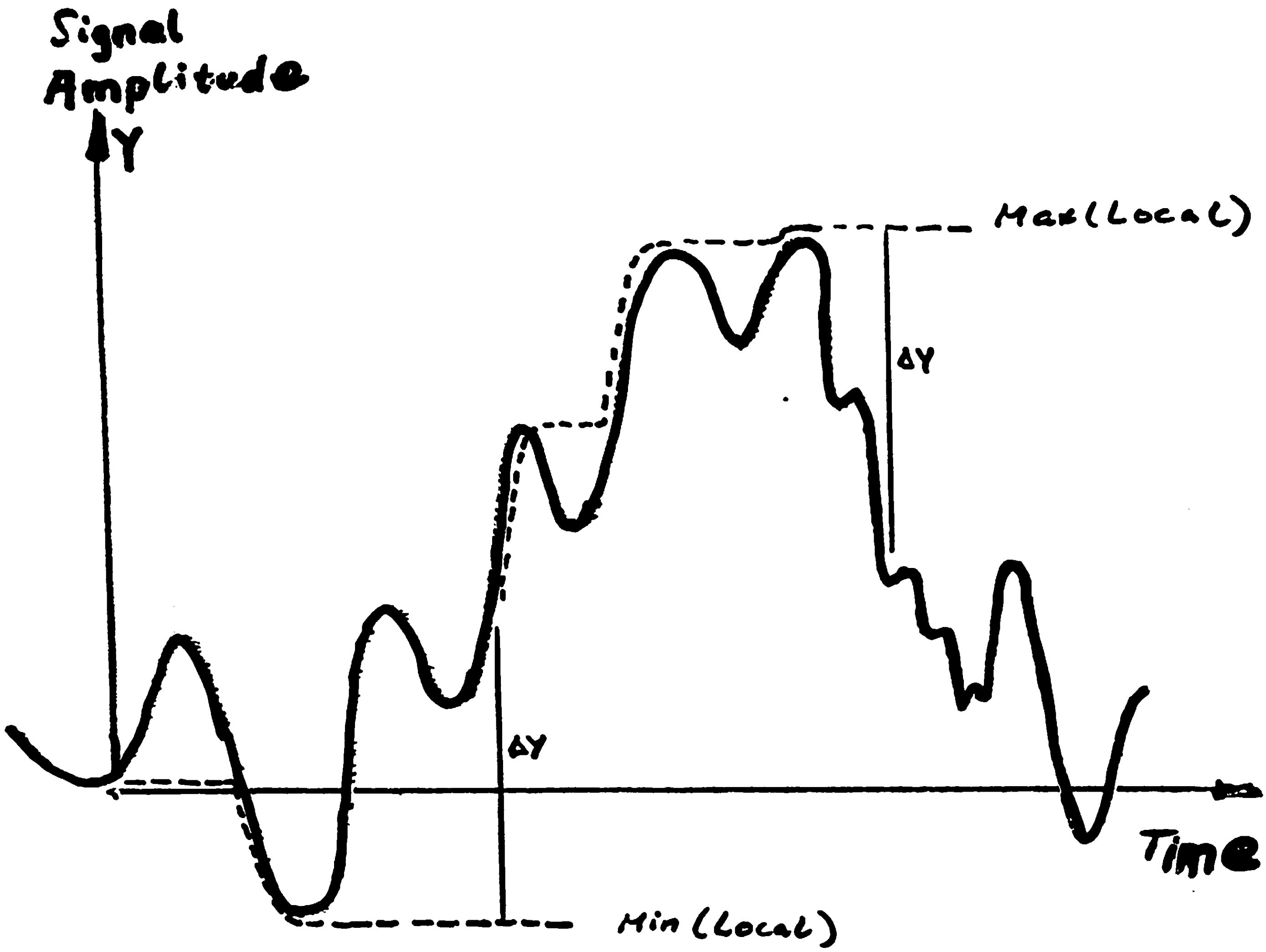


Fig. 4

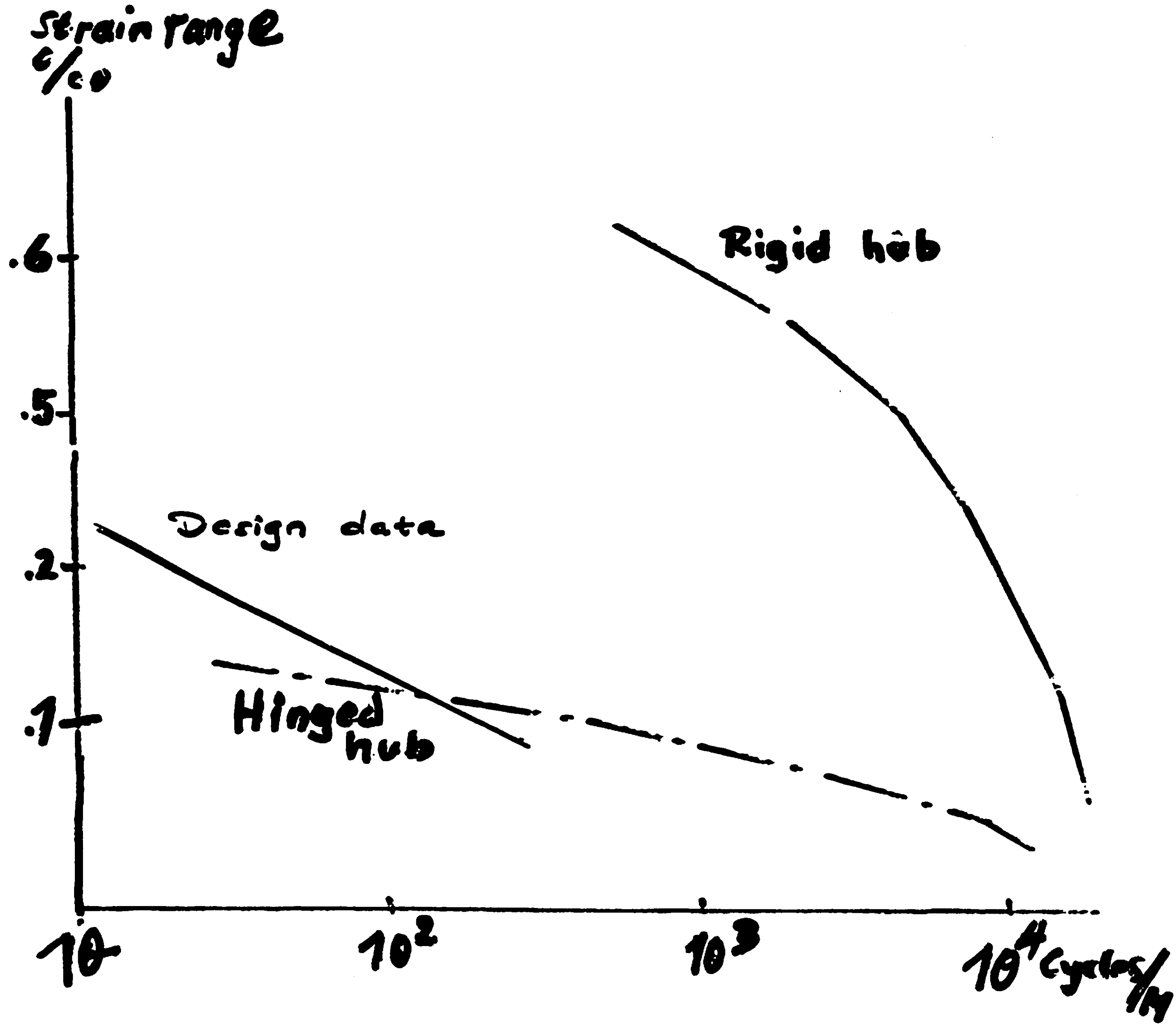
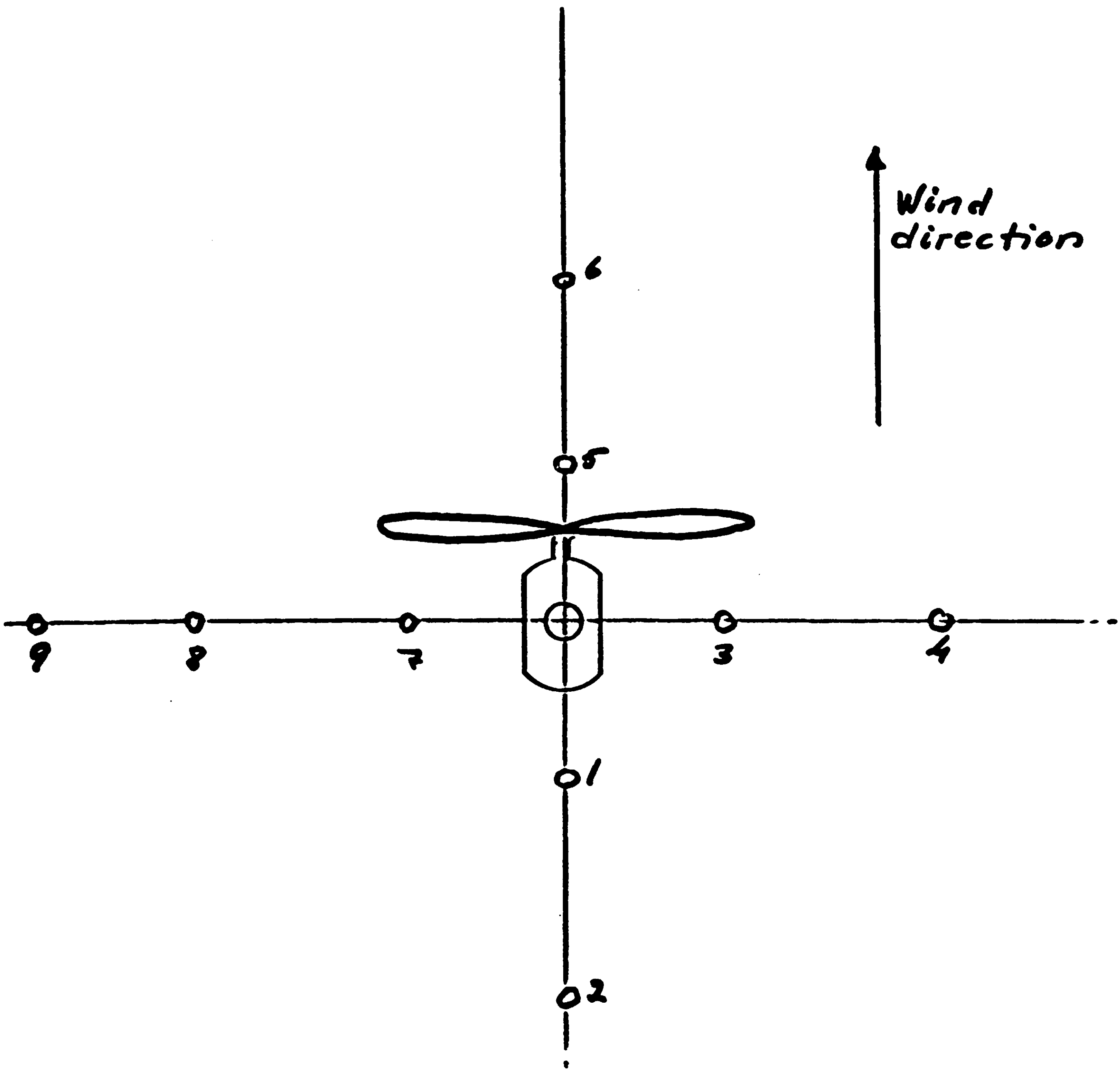

Strain range
%
.6
.5
.2
.1
Rigid hub
Design data
Hinged hub
10
10²
10³
10⁴ Cycles/H

Fig. 5



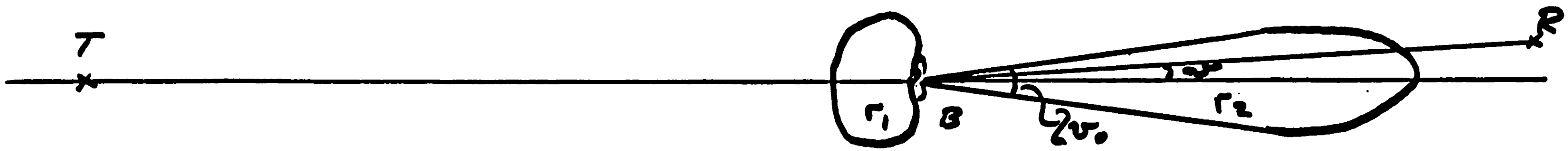
o 1-9 : Microphone Locations

1, 3, 5, 7 12 m from tower

2, 4, 6, 8 100 m — " —

9 300 m — " —

T: Transmitter
R: Reciever
B: Blades



$r_1 \hat{=} r_1 \cos(\pi/2 - v/2)$

$r_2 \hat{=} r_2 \sin \pi x / \pi x$

$x = v/v_0$

At max covering range of T

	r_1 (km)	r_2 (km)	$2v_0$
Metal blades:	2.8	7.2	2°
GRP+thin wire:	0.5	2.6	2°
Non conducting:	0	0	2°

FIG. 6

FIG. 7

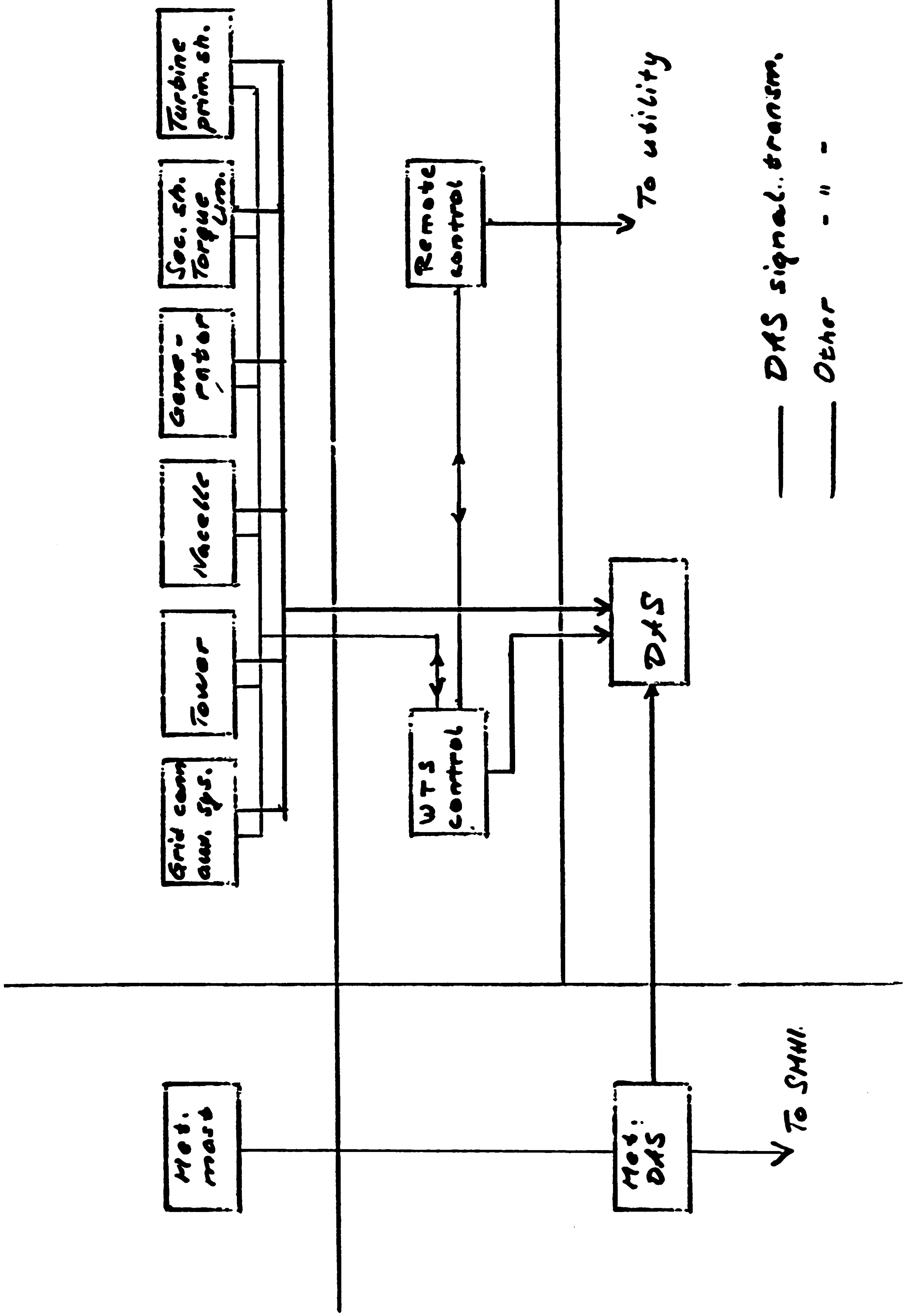
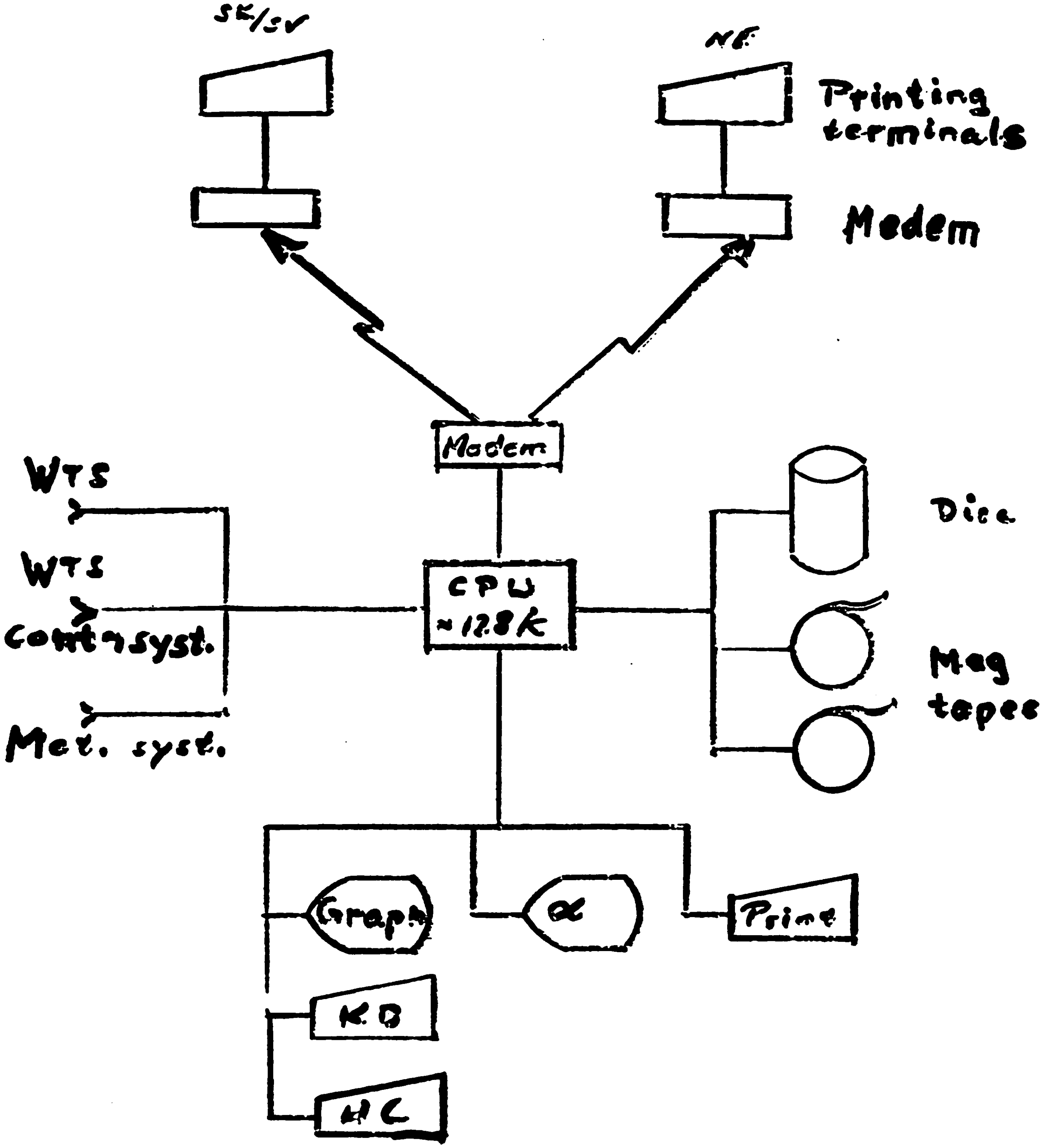

Turbine prim. sh.
Sec. sh. Torque lim.
Gene-rator
Nacelle
Tower
Grid con. aux. sys.
Remote control
To utility
WTS control
DAS
Met. mast
Met. DAS
To SMHI
DAS signal transm.
Other " "

Fig. 8


SK/SV
NE
Printing terminals
Modem
Modem
WTS
WTS
Contr. syst.
Met. syst.
CPU
≈128K
Disc
Mag tapes
Graph
α
Print
KB
HC

METEOROLOGISKA DATA FRÅN MAST *METEOROLOGICAL DATA FROM MAST.*

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätonoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl. redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rådata	Datalagring: Beräknade	Anm.
ndhastighet	2.11 2.13 2.21 2.31	Kont	0.2				*Wind*	*speed*	6x2+1=13			v, v^2, v^3 per 10 min	Viktat, sammanslaget medelvärde för P= f(v) Varaktighetskurvor		x	Dubblerade - en väljs för varje nivå beroende på vindriktn.
-"-	4.1	10 min	-"-			x			-"-					x		Mätkampanjer
-"-	2.22,3.1	10 min	-"-						-"-					x		
n. ..astighet, ..rbulens	3.11	60 min 1)	20	4			*Wind turbu*	*speed, lence*	3x3 riktn.=9					x 2)		3 nivåer
-"-	3.1	Kont	20	4								Turbulensgrad (=variansen)			x	
ndriktning	2.11 2.13	Kont	0.2				*Wind*	*direction*	2			10 min-medelvärde	Varaktighetskurvor		x	
-"-	2.22,3.1	10 min	-"-						"					x		Mätkampanjer
-"-	4.1	10 min	-"-			x			-"-					x		
fttemperatur		Kont	1/10min				*Air*	*temp.*	3					x		På mark, i navhöjd, i toppen
f ..iktighet		Kont	1/10min			x	*Air*	*moisture*	1					x		Navhöjd
bildningsrisk		Kont	Indikering				*Indication of ice*	*formation*	1			Redovisning av tidpunkt			x	På blad i stället

1) Turbulensmätningar görs samtidigt med mätningar av töjningar, laster m.m. En kortare period kan då vara aktuell.

2) I separat datainsamlingssystem.

Appendix 1.

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TURBIN OCH PRIMÄRAXEL   Turbine & primary shaft

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav Mätn./s.	Frekvensinnehåll Hz	Mätonoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare Antal (exkl. redundans)	Redundans	Övr. givarkrav	Beräkningar On line	Utvärdering	Datalagring Rådata	Beräknade	Anm.
ladvinkel	3.1	5 min		0-20	± 0.1°		Pitch	angle	2 2)	x			Vinkelhastighet Vinkelacceleration	x		
-"-	4.1	5 min		0-20		x			2 2)	x				x		
lappingvinkel	3.1	5 min	10				Flapping	angle	2 1)	x			Kraftvektorns riktn.	x		
...ngar i ...lad o bladrot	3.1	1 min		0-20			Strains and blade	in blades root	2) 3) ca 56	x 4)			Frekvensanalys, spänningar, moment	x		
-"-	4.1	1 min		0-20		x			ca 6	"				x		
-"-	3.12	Kont		0-20					ca 6	"		Lastväxlingar uppdelat på ca 20 nivåer	Sammanställning för längre perioder		5) x	
...öjningar i ...av	3.1	1 min		0-20			Strains	in hub	ca 10 2)	x			Moment, spänningar, frekvensanalys	x		
-"-	4.1	-"-		0-20		x			ca 10 2)	"				x		
-"-	3.12	Kont		0-20					ca 4	"		Lastväxlingar, uppdelat på ca 20 nivåer	Sammanställning för längre perioder		5) x	
...ast i bladvinkelservo	3.1	1 min		0-20			Load in angle	pitch servo	4 2)	x			Som för blad	x		
-"-	3.12	Kont		0-20					4	x		Lastväxlingar			x	
...ent i primäraxel	3.1 2.14 2.22 3.22	10 min		0-20			Torque mary	in pri- shaft	1	x			Effekt ur moment x varvtal	x		
-"-	3.12	Kont		0-20					1	x		Lastväxlingar			x	
-"-	4.1	10 min		0-20		x			1	x				x		

1) Vid flappingnav. 1 givare vid gungbrädesnav
2) Konstruktionsberoende
3) 5 snitt à 10 givare längs bladet samt 8 st i bladrot.
4) Redundanta givare i blad 2
5) Lagrat per 10 min.

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SECONDARY SHAFT & TORQUE LIMITER

SEKUNDÄRAXEL, EV. MOMENTBEGRÄNSARE

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätonoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rådata	Datalagring: Beräknade	Anm.
Vridmoment i sekundäraxel	3.11 3.22 2.22 (2.14)	10 min		0-20			Torque shaft.	in sec.	1	x			Mekanisk effekt	x		
-"-	4.1	10 min		0-20		x								x		
Ev. vridmoment i axel mellan växel och momentbegränsare	3.11 2.22	10 min		0-20			Torque after Limiter	in shaft torque	1	x			Mekanisk effekt	x		Konstruktionsberoende
-"-	4.1	10 min		0-20		x								x		

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Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätonoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl. redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rådata	Datalagring: Beräknade	Anm.
indhastighet	2.11,2.13 2.21 2.31	Kont	1				Wind	speed	1			v,v^2,v^3 per 10 min	Undersökning av användbarheten av denna vindmätning för styrning av aggregatet		x	
-"-	3.1, 2.22	10 min							1					x		Mätkampanjer
-"-	4.1	10 min				x			1					x		
ndriktning l. gondol	2.11,2.13	Kont	1				Wind in rela nacelle	direction tion to	1			10 min medelvärde Riktning rel.mark			x	
-"-	2.22 3.1	10 min	-"-						-"-					x		I samband med mätkampanjer
-"-	4.1	10 min	-"-			x			-"-					x		
inkelläge för urbin	2.14 2.22				1°		Angular	position					Mekanisk effekt			
vtal,vinkel-stighet,vin-lacceleration	3.11 3.22	5 min	10				speed leration	and acce- , turbine	3[1)]	x				x		
o	4.1	5 min	-"-			x			-"-	x				x		
celerationer primäraxel-ger	3.11 3.22	5 min		0-20			Accele in main	ration bearings.	2x3				Frekvensanalys	x		x, y och z-riktning
o	4.1	-"-		0-20		x			-"-							
celerationer generator-...ent,växel-...a	3.11 3.22	5 min		0-20			Accele in gen suppor machine gear box	rations erator, ting beams ry and .	2x3 flyttbar				Frekvensanalys	x		x,y och z-riktning
ningar i ...infundament ... gondol	3.11 3.22	5 min		0-20					ca 10				Spänningar o.s.v. Frekvensanalys	x		
-"-		5 min		0-20		x	Strains ting be and nacelle	in suppor- ams	-"-					x		
-"-	3.12	Kont		0-20					ca 2		—	Lastväxlingar			x	

1) 3 signaler från gemensam givare

TORN *Tower*

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Frekvensinnehåll Hz	Mätnoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl redundans)	Redundans	Övr. givarkrav	Beräkningar: On line	Utvärdering	Datalagring: Rådata	Beräknade	Anm.
idningsvinkel, inkelhastighet i gondol	2.12 3.11 3.23	10 min	1		1°		*Yaw angle and speed*		2					x		Samma givare för vinkel o vinkelhastighet
-"-	4.1	10 min	1		1°	x								x		
ter i sidmekanism	3.11 3.23	10 min		0-20			*Loads in yaw mechanism*		1[1)]					x		
-	3.12	Kont		0-20								Lastväxlingar			x	
celerationer torn	3.11 3.24	1 min		0-20			*Accelerations in tower*		2 nivåer x 3 riktn = 6					x		
jningar i n		1 min		0-20			*Strains in tower*		3 nivåer à 5 givare = 15[1)]					x		Lastväxlingar?
atiskt lufttryck		Kont	1/10 min		0.2%		*Static air pressure*		1							
celerationer fundament	3.24	1 min		0-20			*Acceleration in tower foundation*		3[3)]					x		Ständig övervakning av nivåer?

) Konstruktionsberoende
) Stålplattor pa ca 30 ställen, symmetriskt utplacerade
) " " " 15 " " "

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GENERATOR *GENERATOR*

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätnoggrannhet	Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rådata	Datalagring: Beräknade	Anm.
Aktiv och reaktiv energi till/från gen.	2.11	Kont	1/10 min		2.0%		*Active/ energy*	*reactive to/from generator.*	2				Energiproduktion Varaktighetskurvor	x		
Aktiv och reaktiv effekt till/från gen.	4.1	10 min		0-2	1.5%	x	*Ditto*	*power*	2					x		
-"-	2.22	1 min		0-2	1.5%									x		
Fasspänning vid generator	2.22	1 min		0-200	1.5%		*Phase at generator*	*voltage*	2					x		
-	4.1	?	?		1.5%	x								x		
Fasströmmar	2.22	1 min		0-200			*Phase*	*currents*	1					x		
-"-	4.1	?	?			x								x		
Lastvinkel	2.22	1 min		0-2			*Load*	*angle*	1					x		
Fasvinkel							*Phase*	*angle*	1							Nödvändig mätni Beräknas?
Generatorvarvtal (vinkelläge, vinkelacceleration)	2.22	1 min		0-200	0.5%		*Generator speed (angular position,*		3					x		3 signaler från gemensam givare
-"-		10 min	10		0.5%	x	*speed and acceleration)*		1 (enb. varvtal)					x		
Temperatur i statorlindningar	4.2 4.1		Kont		± 2 K 1)	x	*Temp.*	*stator windings.*	3	x		Temperaturlastspektrum?		x		
	--															

1) Or preferably according to DIN 43760

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NÄTANSLUTNING, HJÄLPSYSTEM GRID CONNECTION, AUXILIARY SYSTEMS

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätnoggrannhet	Mätkrav: Fellogg	Placering Mätpunkt	Typ/fabrikat	Givare: Antal (exkl. redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rådata	Datalagring: Beräknade	Anm.
..tiv och re..tiv energi ..ll/från ..regat	2.11	Kont	1/10 min		1.5%		Active/ energy	reactive to/from WT	2				Energiutbyte	x		
..tiv och re..tiv effekt ..ll/från ..regat	4.1	10 min		0-2		x	Ditto,	power,	2					x		
..tfrekvens	2.22	1 min	1'		0.05%		Grid,	frequency	1					x		
..förbrukning i hjälpsystemet 2)		Kont	1/10 min				Energy tion, systems.	consump- auxiliary	ca 5			Summering till längre mätperiod			x	
~~..tr. brytar..likeringar, .. "Styr- och ..lersystem"~~																

2) Aktuella hjälpsystem: bladvinkelreglering, sidvridmekanism, uppvärmning och kontrollsystem

Mätstorhet	Utvärderingsuppg (App. 3)	Mätperiod (kontinuerlig/mätkampanj)	Mätkrav: Mätn./s.	Mätkrav: Frekvensinnehåll Hz	Mätkrav: Mätonoggrannhet	Mätkrav: Fel-logg	Givare: Placering Mätpunkt	Givare: Typ/fabrikat	Givare: Antal (exkl. redundans)	Givare: Redundans	Givare: Övr. givarkrav	Beräkningar: On line	Beräkningar: Utvärdering	Datalagring: Rå-data	Datalagring: Beräknade	Anm.
riftmod för gregat	2.31	Kont	Indikering				WTS of ope	mode ration	ca 6			Tidpunkt för byte av mod, samt vilken övergång som skett	Summering av tid i resp. mod			
iftindikering r större ponenter	2.31	Kont	Indikering				Status tions	indica large components	ca 5			Drifttidberäkning				
lsignaler	4.1	Kont	Indikering				Fault tions	indica	-ca 25			Redovisning av signaler och tidpunkt				
iga driftindikeringar	4.1	Kont	Indikering			x	Misc. tions	indica	ca 10							T.ex. brytarindikeringar
rvärde för dvinkelreglering etc		5 min		0-20		x	Set pitch	point control	ca 4					x		
t- och övervakningssignaler	4.2	Kont	1/min			x	Misc. signals	analogue						x		Temperatur i växellåda e.d. nivåer m.m.

Measuring Program for two Windmills at Nibe, Denmark

by

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Boone, North Carolina, USA

1. Summary:

After af short description of the two windmills being built at Nibe, Denmark, the main strategy for the measuring program is outlined.

The physical lay-out of the measuring system is also described. Signals from about one hundred sensors are going to be processed in a PDP 11/34 conputer, and the computed values are to be displayed on a printer/plotter or a CRT-screen. At the time of writing the mills have not been put into final operation, so practical results are not yet available.

2. Windmill A and B

The technical specifications of the two windmills being built at Nibe by the Wind Power Program of the Ministry of Commerce and the Electricity Utilities in Denmark are summarized in tabel 1. The mills are rather similar to one another, the main difference being the stayed/nonstayed bladeconstruction and the type of regulation.

The site for the Nibe mills is shown on figure 1, which also indicates the mean wind velocities in Denmark for a 30-year period. The site is at an inland position, which generally would imply a low mean wind velocity, but in the actual case the wind conditions are supposed to be satisfactory, because of the open waters west of the mills and the flat and open countryside in the other directions, see figure 2, The distance between the mills is app. 200 m, and a meteorological tower is placed between the mills as seen on figure 3.

Figure 4 gives a general view of mill A and B. Both rotors have identical airfoils and a 11^{o} twist. All blades have an outer section made entirely of fibreglass laminate and an inner section made of fibreglass shells attached to a tubular steel beam. The blades on mill A are supported by 9 stays. Mill B has cantilevered blades. This is partly the reason why mill A has stall regulation and mill B pitch control.

A cross section of rotor A and nacelle A is seen on figure 5. As might be seen the blade angle may be changed during operation. In fact the pitch angle of the outer blade section is changeable between + 15 and - 20 degrees. The nacelle rests on a yaw bearing, yawing being controlled by two hydraulic motors and four disc brakes. The blades of rotor B can be changed between - 1 and + 90 degrees.

Figure 6 shows a horizontal cross section of the nacelle and the position of the main components. The power supply to the transducers mounted on the rotor and the higth level signals from the rotor are transmitted by sliprings on the main shaft. The low level signals from all strain gauge bridges are transmitted by a radio frequency carrier system with antennas mounted between the two main shaft bearings (PCM telemetry system).

The towers of mill A and B are identical, see figure 7. Reinforced concrete towers have been used, because this construction seemed to be cheapest and also non-harmful to the upwind rotors. Preliminary tests have verified the calculated eigen-frequency of appr. 1,3 Hz (low tuned towers).

The electrical system is composed of conventionel components, see figure 8. The generators are 6 kV induction generators, which feed into the public grid through a 6/20 kV transformer. The high tension components are placed in high tension rooms at ground level and inside the towers, see also figure 7.

The control system is responsible for the fully automatic operation of the mills. In each of the mills two microprocessors execute sequence control respectively closed loop control operations. A third CPU takes care of the mutual communication between the two control processors.

Figure 10 shows the details of the operating and display panel. To the left a set of alarms is placed. In the middle push buttons and status indications for start and stop of rotor respectively yaw system is placed. To the right 16 thumb wheels make it possible for the operator to change certain control parameters.

The control of the rotor system follows the pattern shown on the graphs on figure 11. Mill A has two discrete pitch angles. Mill B varies the pitch angle continously as shown on the graph. Both of the mills produce 630 kW at full power.

In this case both of the windmills are prototype mills. It is therefore difficult to seperate the costs between development costs and design and construction costs. The summary on figure 12 should, consequently, be treated accordingly.

3. Measuring program.

3.1. General purpose.

After commissioning an extensive measuring programme will be put into operation in order to clarify all aerodynamic, mechanical and electrical properties of the mills.

For practical reasons the measuring programme has been devided into a number of stages, see figure 13.

Stage 0 aimes at obtaining provisional data about operation and efficiency of the mills. In this case only signals from the permanently installed sensors are used, and the recording medium is a six-channel fast speed analog recorder. A conventional xy-recorder with averaging input circuits will be used to record the power curve (relationship between windspeed and active electric power). Stall observations may succesfully be carried out by airfoils attached to one of the blades of mill A.

Stage 1 through 3 are all performed by a computerized data collection and evaluation system. Most of the sensors are specific to this system, but some are shared with the previously mentioned operational system.

Stage 1 may shortly be decribed as spot checks, i.e. specific investigations of specific problems. Included in this is also verification of designparameters and assessment of the most importent operational characteristics. As far as possible most of the dataevaluation should be made on-line in order to avoid excessive amounts of tapes for later troublesome interpretation.

Stage 2 is also a sort of spot checks, but in this case the innestigations are supposed to be of a more detailled character. Besides, more considerations are taken into account. This relies for instance to the study of wind qusts and also to a comparison of the performance of the two windmill, which are very much alike but differ with regard to control principles (stall respectively pitch control).

Stage 3 may be described as continuous on-line measurements and data evaluations. This applies especially to the recording of averaged wind characteristics and production data, but the possibility of recording accumulated stress in the fibreglass material is also being considered. The reason for this is that the properties of fibreglass material subjected to dynamic load cycles are rather unknown.

3.2. Sensors.

The location of rotor sensors on mill A and B is shown on figure 14 and 15. M1, M2 and M3 are symbols of torsional, edgewise and chordwise moments. N2 is a shear force and T1, T2 and T3 are temperature measurements. All sensors have been calibrated in the laboratory after having been mounted on the blades. Figure 16 shows an example of calibration curves for blade A1.

On two blades - A1 and B2 - 2x6 strain gauges have been installed in non-bridge configurations. These sensors have not been calibrated in advance.

Figure 17 through 21 is the complete list of sensors available to the measuring program. Most of the figures need no further explanation, but it may be relevant to add that the regulation rod mentioned on figure 19 is used to control the pitch angle of the blades. It is placed at the center of the main shaft and its horizontal monement is transferred to the blade system by a mechanical link, see figure 5.

On figure 20 it is said that the data system is prepared to accept input channels from the instrumentation of the towers if such an instrumentation should be needed later on. At the moment an accelerometer is mounted in tower A to give preliminary information about the tower movements.

3.3. Data system.

All sensors from mill A and B and the met.tower are connected to a central data system and processed by a PDP 11 computer before the final results are stored on tape resp. disc or displayed on plotter resp. CRT-screen, see figure 22.

The details of the transmission system is shown on figure 23. As mentioned earlier the sliprings are only used during stage 0. During the later stages the rotor signals will be transmitted by a PCM-system with wireless transmission from a transmitter on the main shaft to a nearby receiver in the nacelle.

The computer room is located in a small wooden office shed, which is temporarely placed at mill A, see figure 24. Next to the computer room is a bigger office room, which may be used by people operating the measuring program.

3.4. Measurements.

At the moment of writing the software system is being finally designed. Figure 25 shows the main principle of data collection during stage 3, which is going to be in operation continuously. During the slow scan period most of the sensors are sampled, and mean values and variances are stored for later presentation. During the fast scan periods only certain rotor signals are processed in order to determine resonance frequencies and fatigue fenominons in the fibre glass material.

Spot checks, i.e. stage 1 programs, may be able to operate parallel to stage 3 programs, but to a limited extent stage 1 programs may interrupt stage 3 programs. That means that the statistical values must not be damaged by too frequent interruptions.

More details about the software system is to be given at a later occasion.

4. Economics.

The total cost of the measuring system can not be given at the moment, because the extent of stage 2 is not fixed. In fact stage 2 has been postponed.

Figure 26 shows the budget for the periode 1978-1980. It should be self-explanatory. If figure 26 is compared with figure 12, it is seen that the total cost of the measuring program is of the same orden of magnitude as one 630 kW windmill.

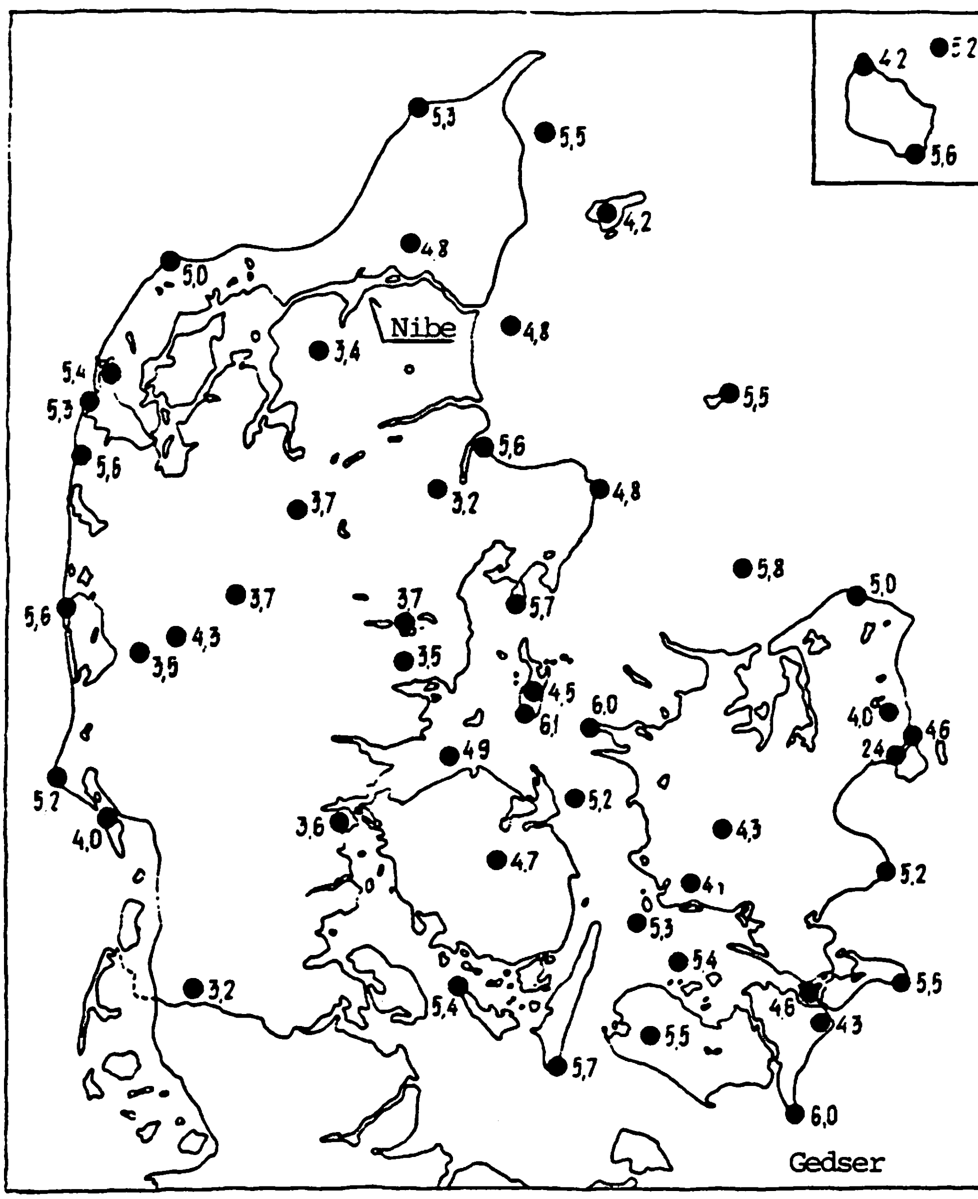
Poul Nielsen

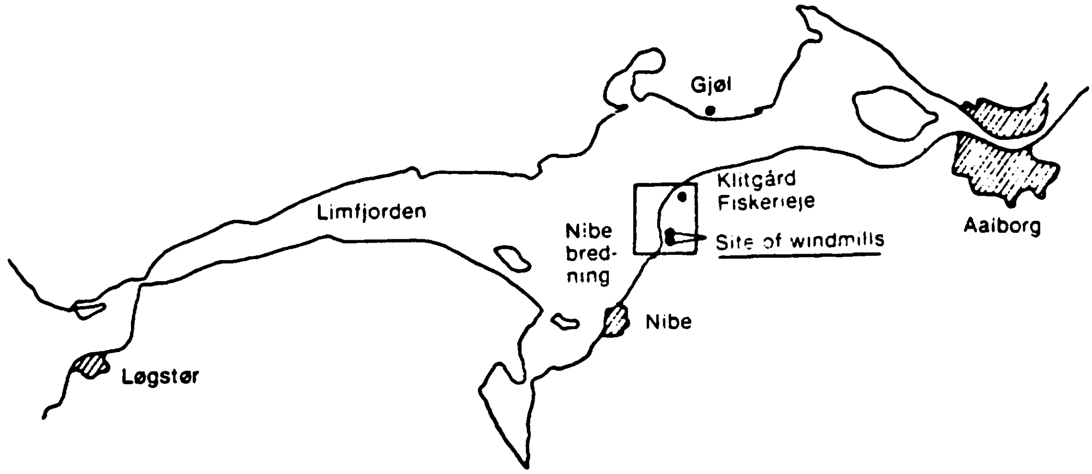
Technical specifications for mill A and B.

	Mill A	Mill B
System life	25 yr.	25 yr.
Tower, type	Corcrete	Corcrete
- , height	42 m	42 m
Rotor, type	Stayed	Non-stayed
- , hub height	45 m	45 m
- , diameter	4o m	4o m
- , location	Upwind	Upwind
- , tilt angle	6 deg	6 deg
- , cone angle	6 deg	6 deg
- , velocity	33.8 rpm	33.8 rpm
Blades, number	3	3
- , material	steel,glassfibre	steel,glassfibre
Nacelle, type	Conical	Conical
- , yaw rate	o.4 deg/s	o.4 deg/s
Gearbox, type	Conventional	Conventional
- , ratio	1:44.85	1:44.85
Generator, type	Induction	Induction
- , rated power	630 kW	630 kW
- , velocity	1516 rpm	1516 rpm
- , voltage	3x6 kV,50 hz	3x6 kV,50hz
Regulation, type	Stall regulation	Pitch control
- , range	+15 to -20 deg.	+90 to -1 deg.
- , max speed	6 deg/s	8 deg/s
- , normal	1 deg/s	6 deg/s
Wind, cut-in speed	5 m/s	5 m/s
- , rated -	13 m/s	13 m/s
- , cut-out -	25 m/s	25 -/s
Estimated production	1.9 GWh/yr	1.9 GWh/yr
Rated spec. power	500 W/m^2	500 W/m^2

Tabel 1.

Mean Wind Velocity, m/s Year 1931-60




Gjøl
Limfjorden
Klitgård
Fiskerleje
Site of windmills
Aalborg
Nibe
bred-
ning
Nibe
Løgstør

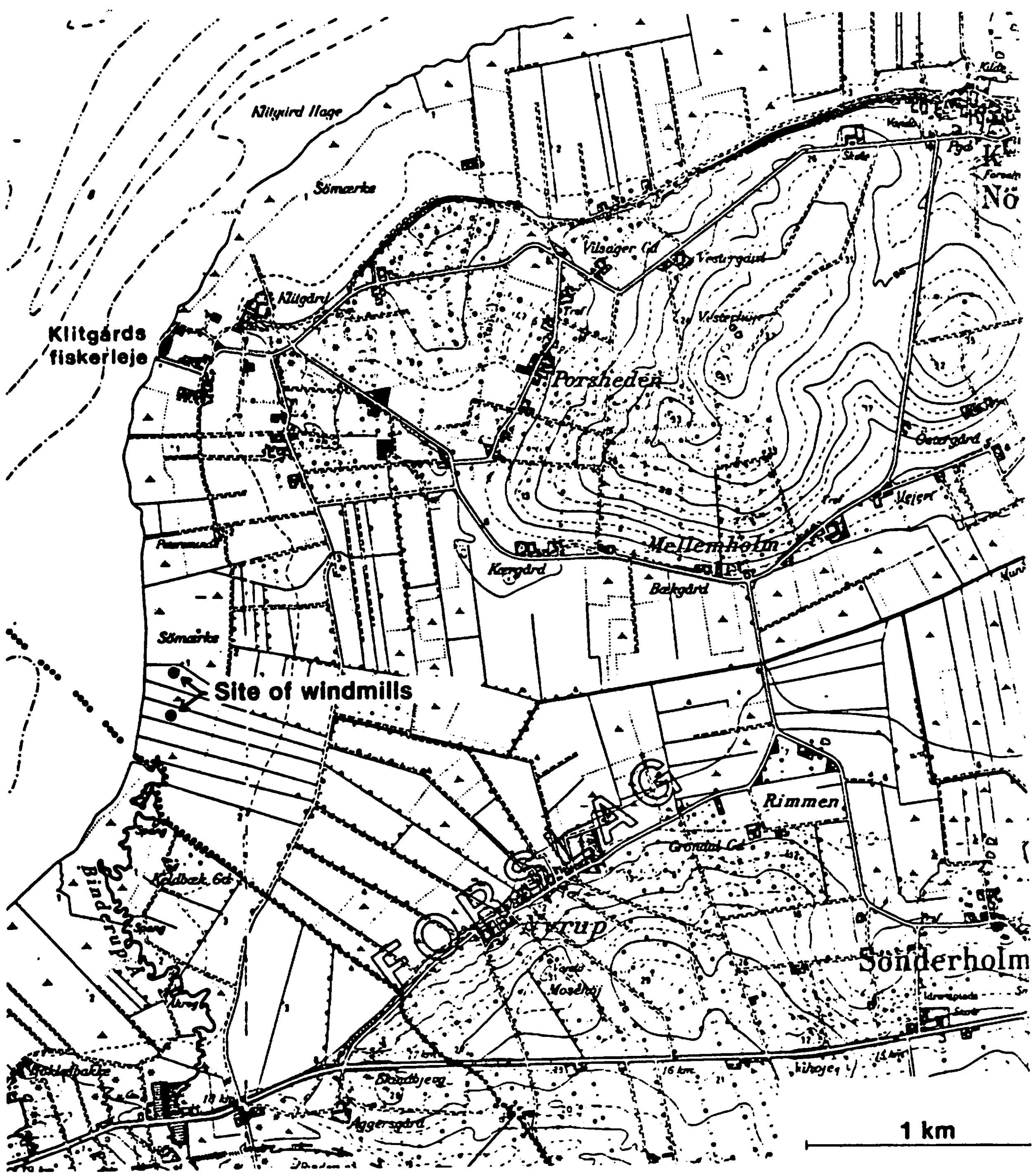

Klitgårds
fiskerleje
Site of windmills
Porsheden
Mellemholm
Rimmen
Sönderholm
1 km

Figure 2

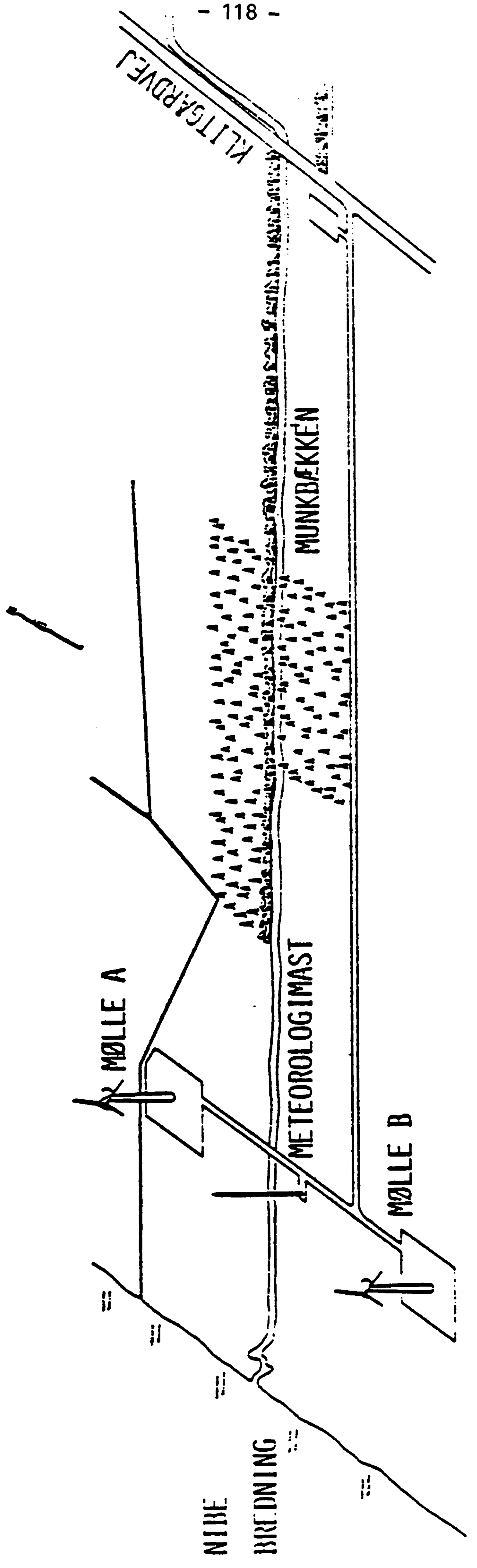

KLITGÅRDVEJ
MUNKBÆKKEN
MØLLE A
METEOROLOGIMAST
MØLLE B
NIBE
BREDNING

Figure 3

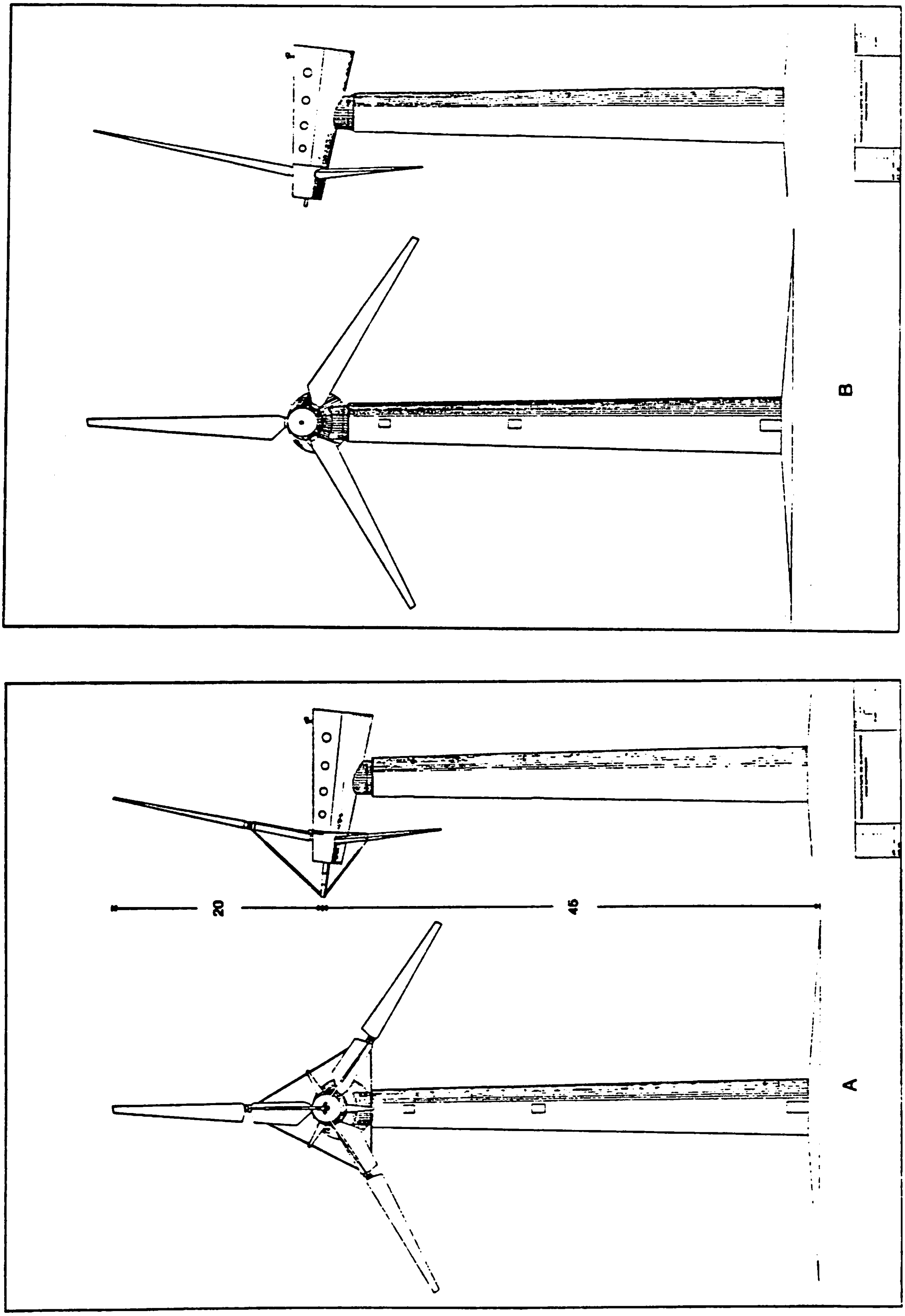
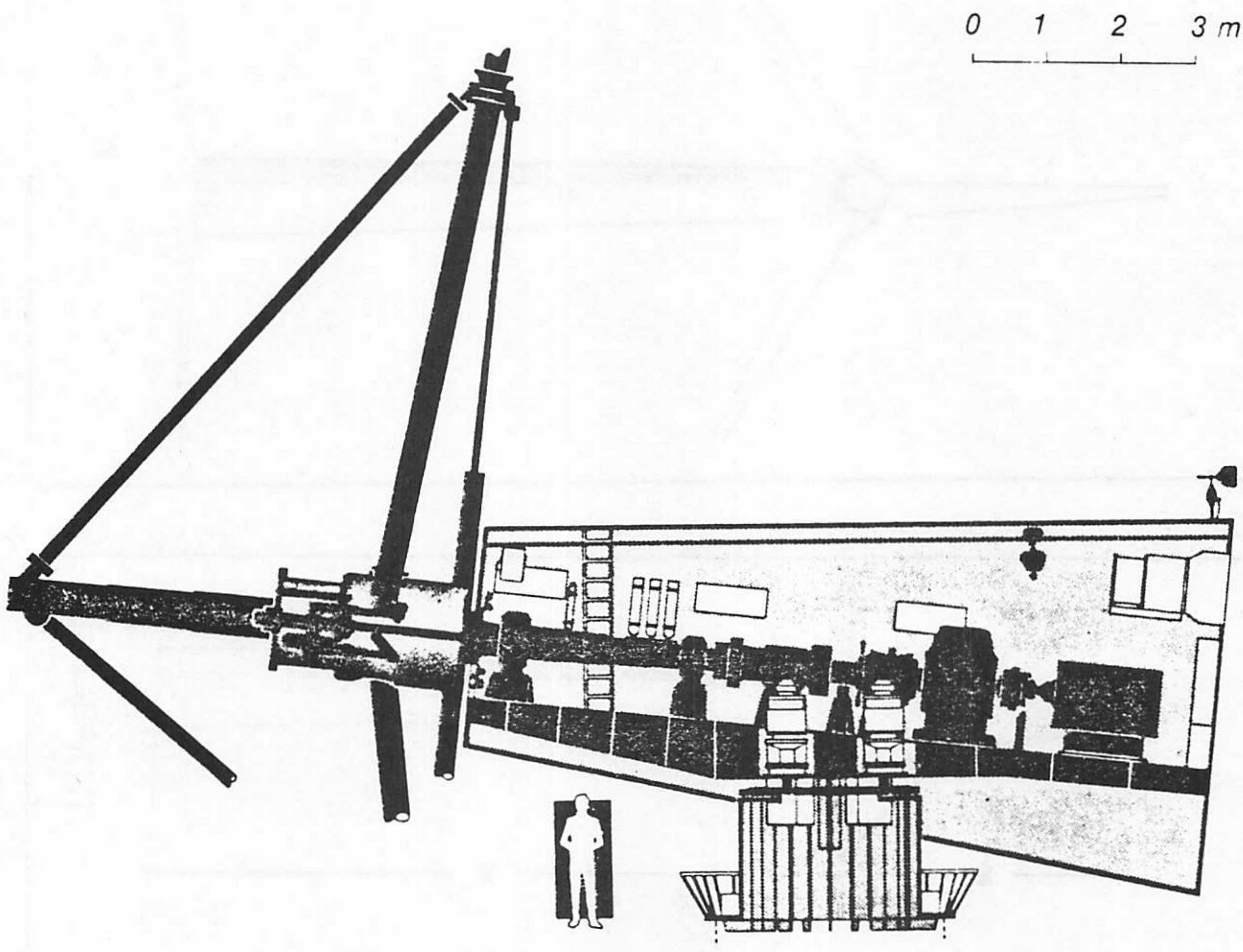


Figure 4



Nacelle with rotor hub (windmill A) and tower top section.

Figure 5

1. Main shaft bearings
2. Main shaft
3. Hydraulic cylinder
4. Coupling
5. Gearbox
6. Coupling
7. Bearings
8. Disc brakes
9. Coupling (breakable)
10. Generator
11. Auxiliary supply
12. Hydraulic system
13. Microprocessor
14. Terminal connections and relays

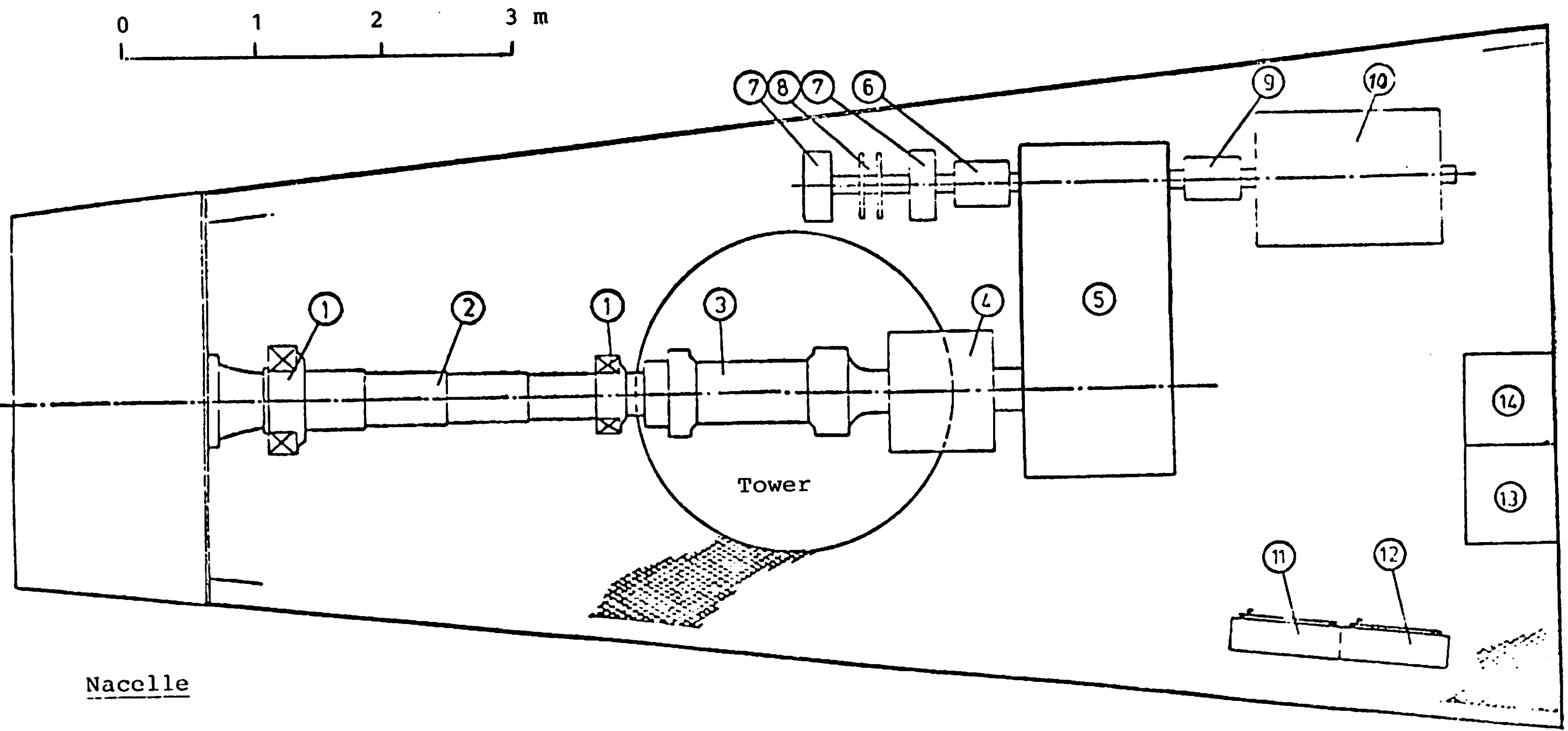
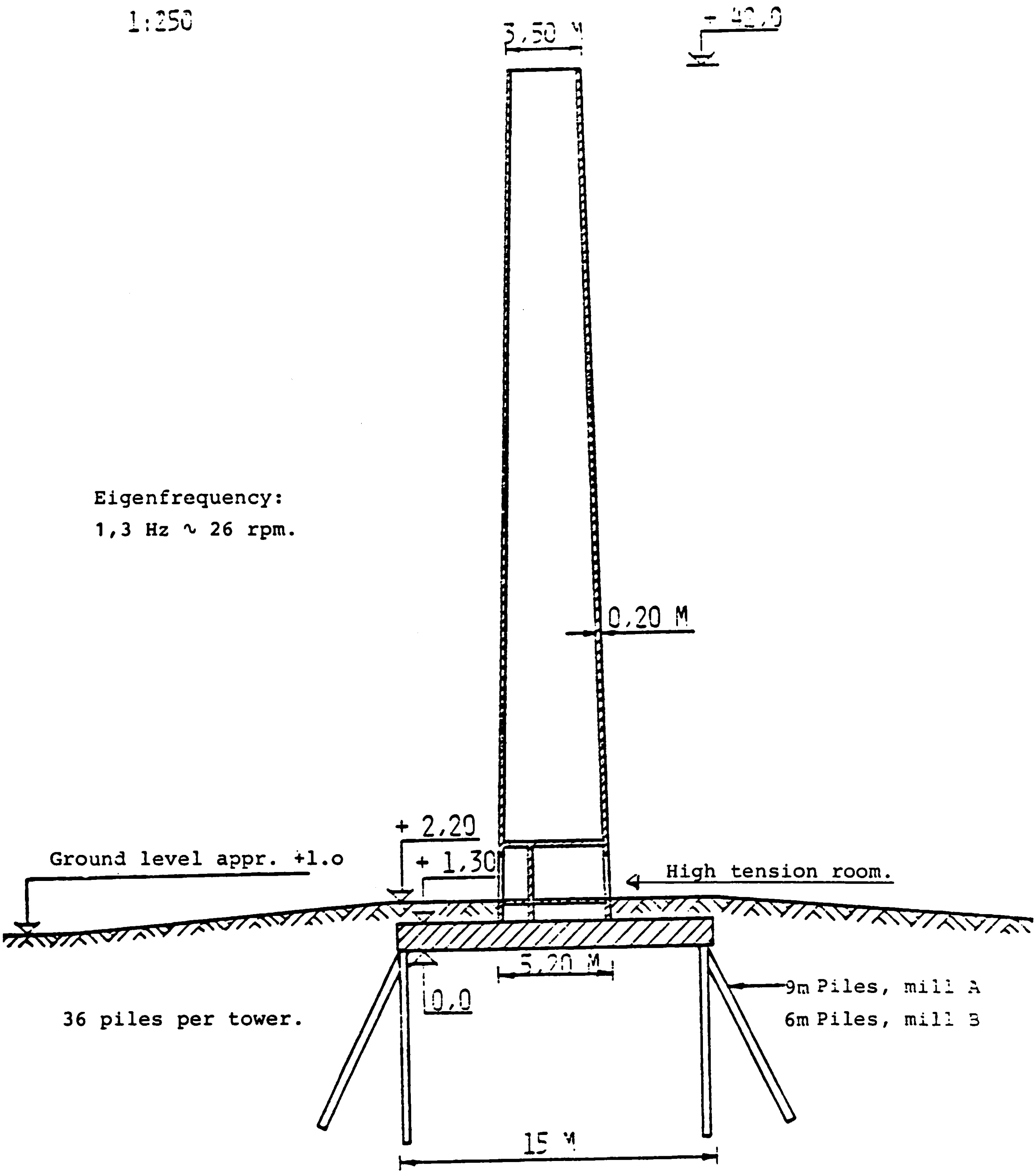


Figure 6 Nacelle

1:250



Concrete tower and pile foundation.

Figure 7

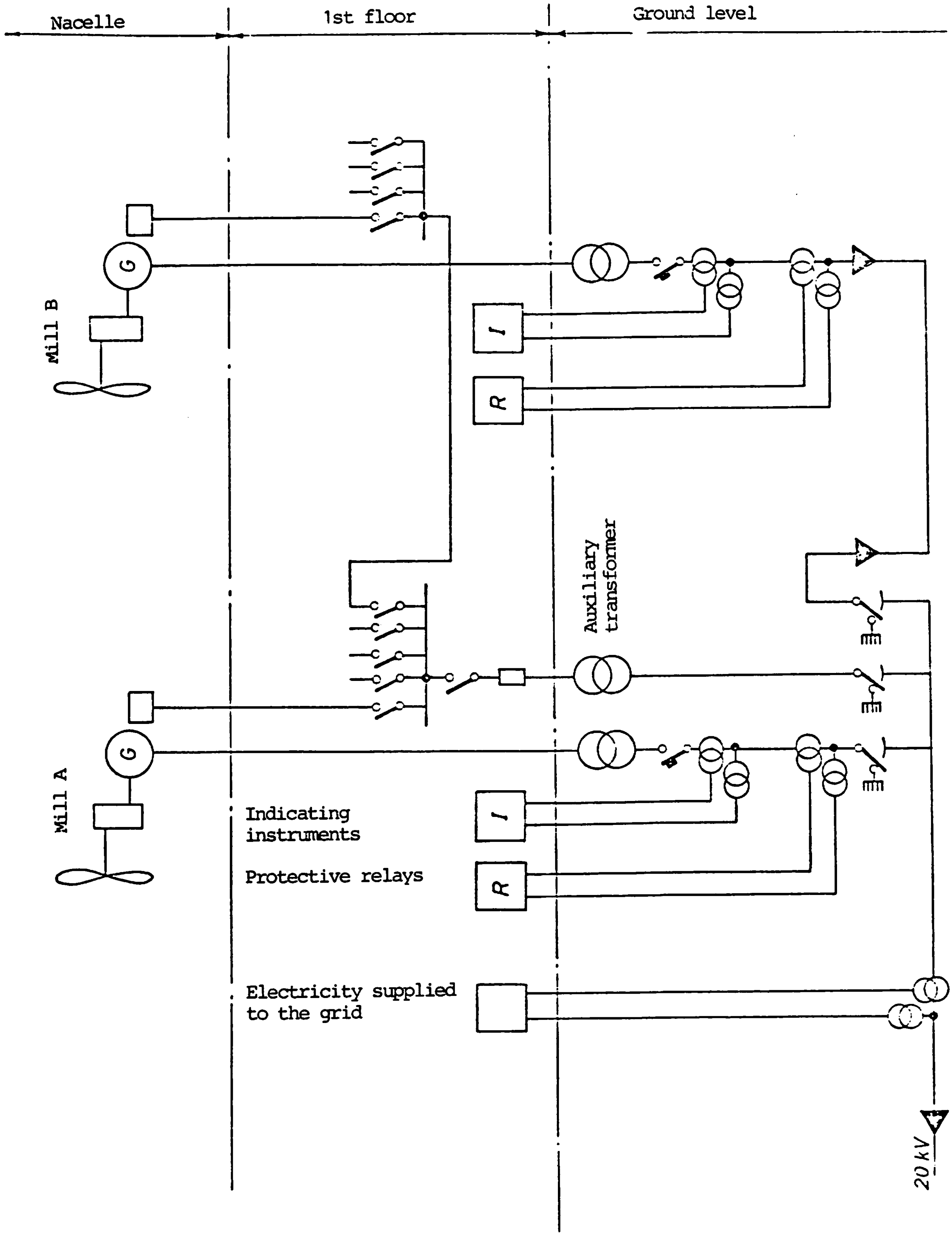

Nacelle
1st floor
Ground level
Mill B
Mill A
G
G
I
R
I
R
Auxiliary transformer
Indicating instruments
Protective relays
Electricity supplied to the grid
20 kV

Figure 8

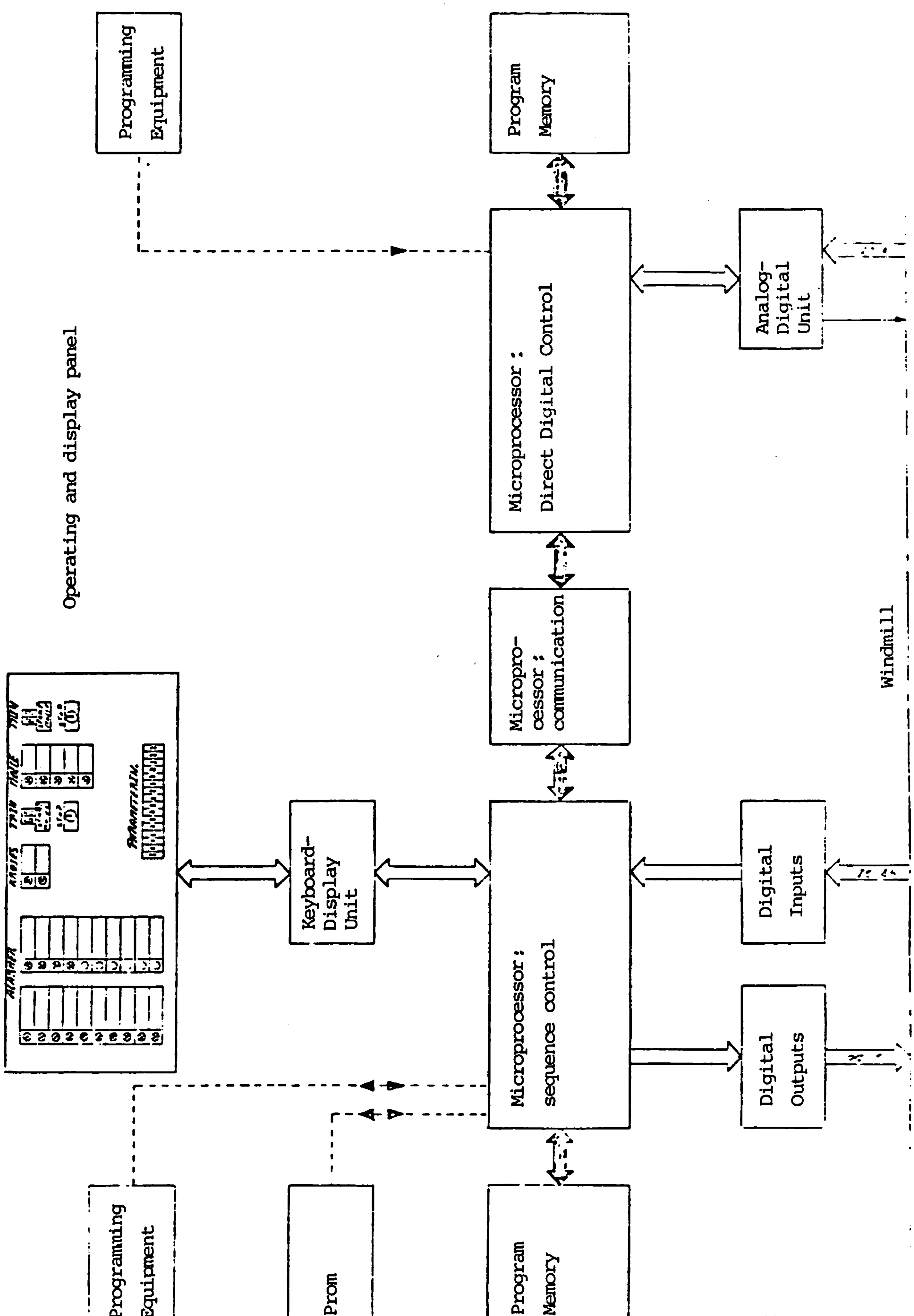
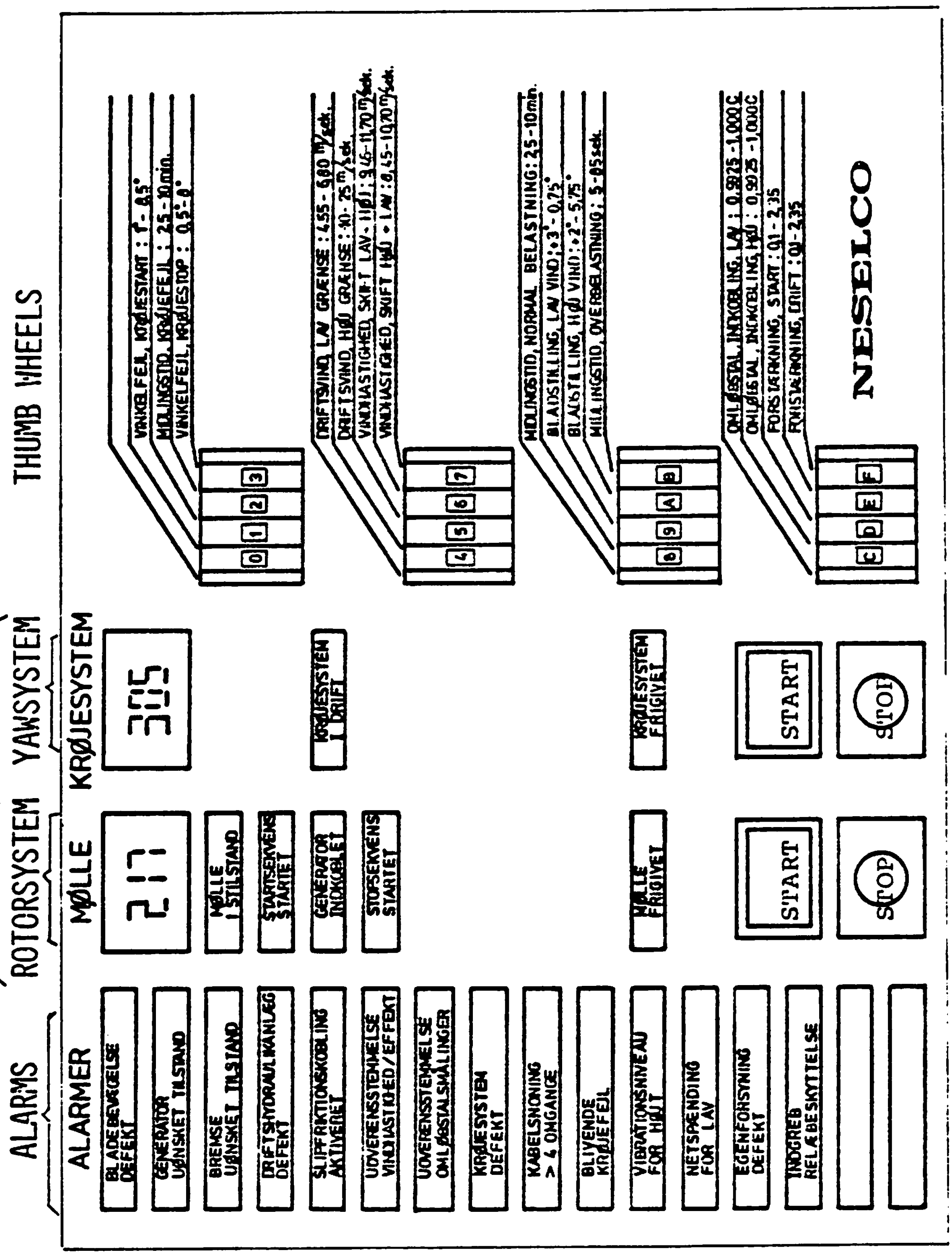
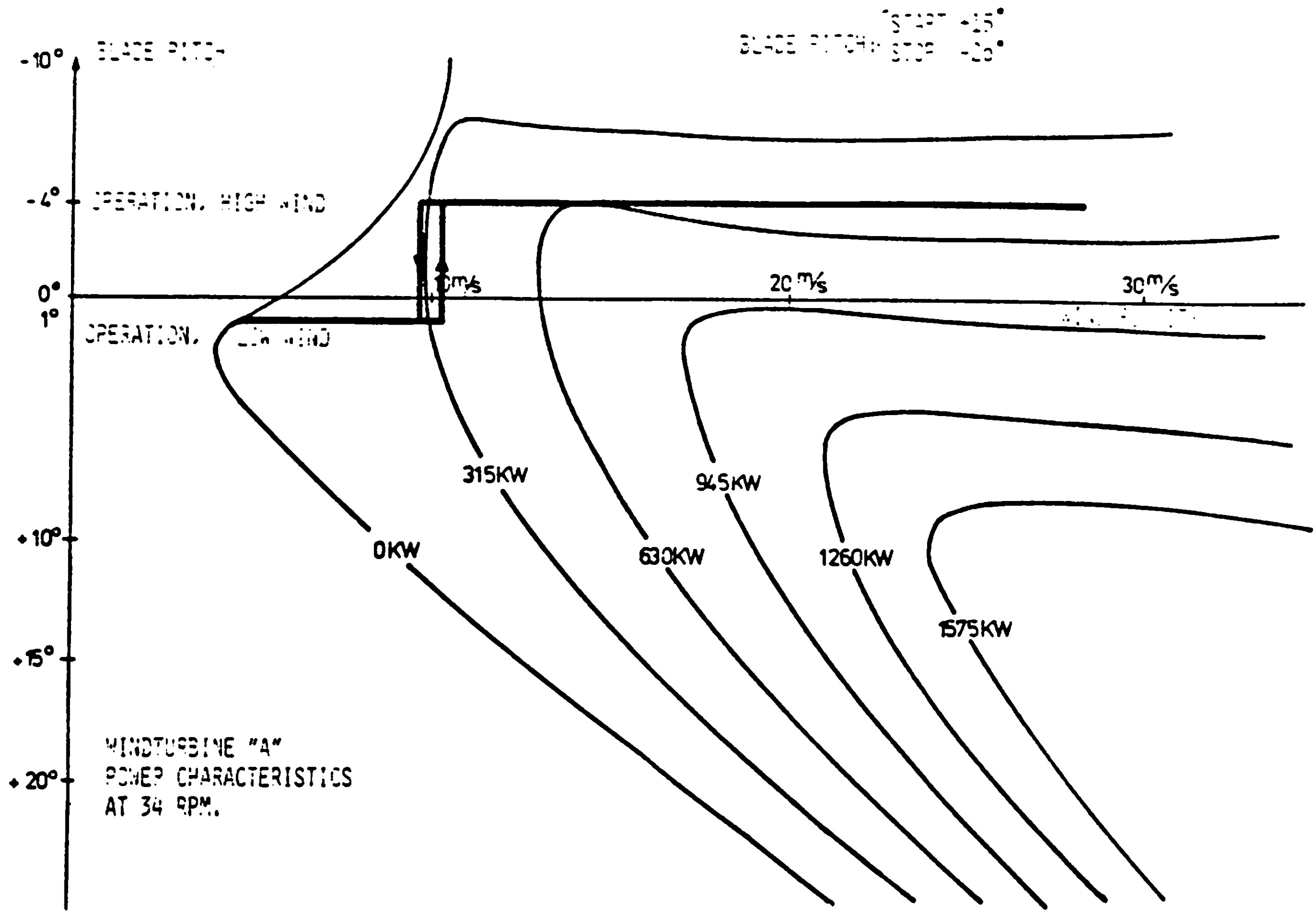

Operating and display panel
Programming Equipment
Program Memory
Microprocessor : Direct Digital Control
Analog-Digital Unit
Micropro-cessor ; communication
Keyboard-Display Unit
Microprocessor : sequence control
Digital Inputs
Digital Outputs
Windmill
Programming Equipment
Prom
Program Memory

Figure 9



WINDTURBINE "A"
OPERATING & DISPLAY PANEL

Figure 10


-10°
-4°
0°
1°
+10°
+15°
+20°
20 m/s
30 m/s
315KW
0KW
630KW
945KW
1260KW
1575KW
WINDTURBINE "A"
POWER CHARACTERISTICS
AT 34 RPM.

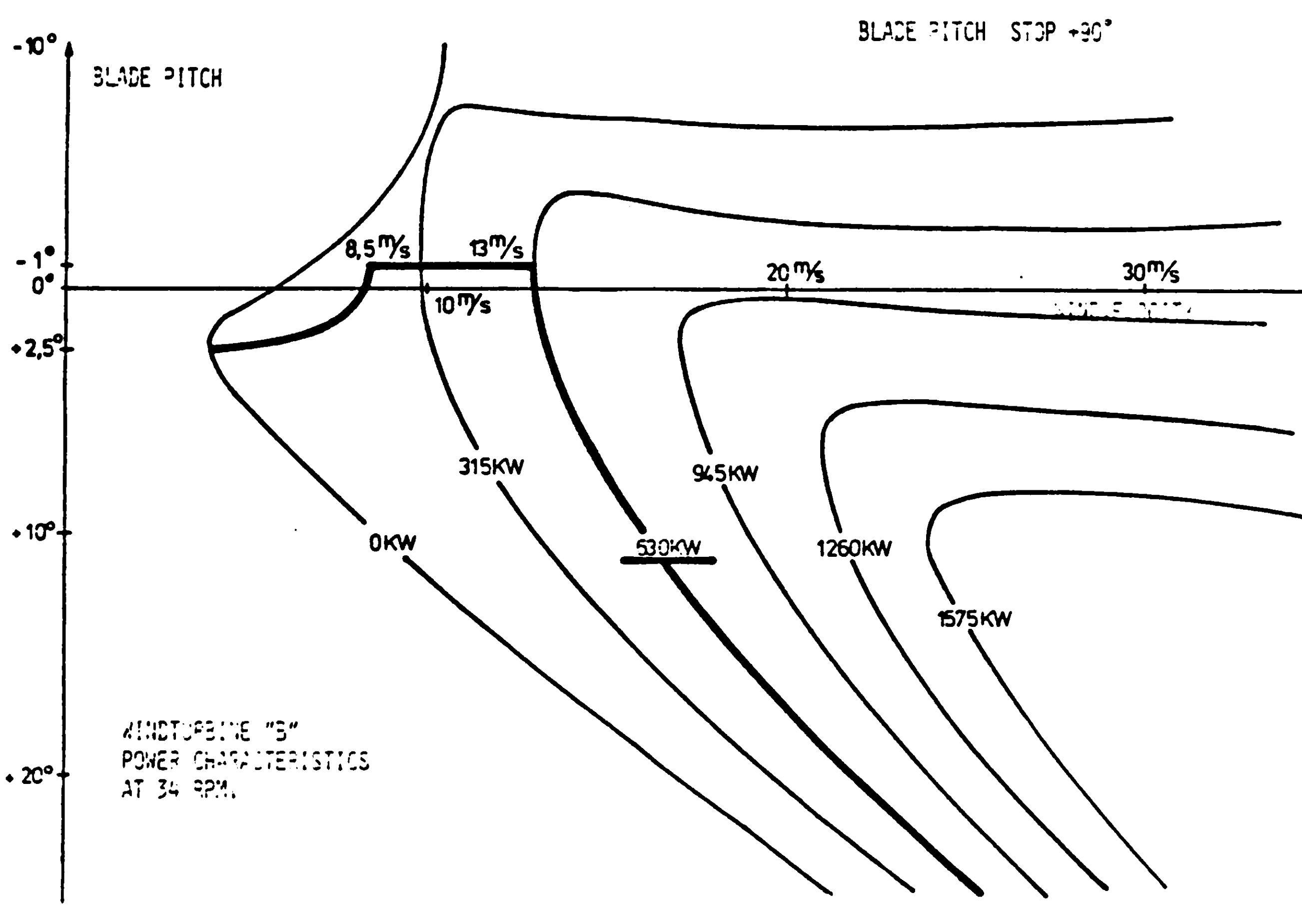

BLADE PITCH STOP +90°
-10°
BLADE PITCH
8,5 m/s
13 m/s
10 m/s
20 m/s
30 m/s
-1°
0°
+2,5°
+10°
+20°
315KW
0KW
630KW
945KW
1260KW
1575KW
POWER
AT 34 RPM.

Figure 11

Summary of design and construction costs for one 630 kW windmill.

		kkr.		k$	
Tower	:	800		152	
Nacelle, incl hub	:	2.500		476	
Gearbox	:	260		50	
Generator	:	135		26	
Rotor	:	500		95	
			4.195		799
Siting	:	250		48	
Electrical	:	650		124	
Div.	:	125		24	
	=		1.025		196
Total	=		5.220		995

Price of Mill A and Mill B almost the same.

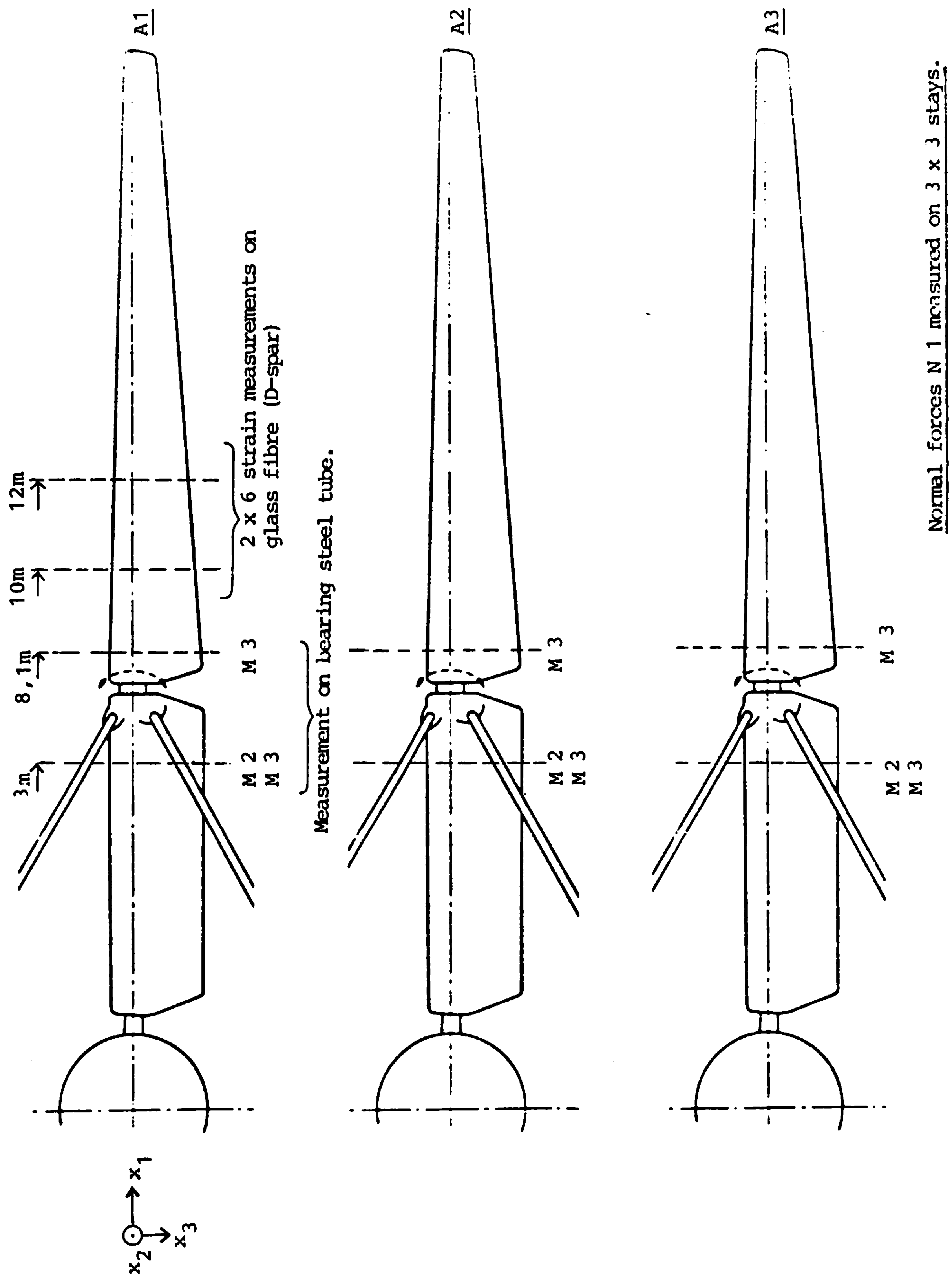
1 $ = 5,25 d.kr.

Figure 12

Stage	1979	1980	1981	Measurements
0				Preliminary data. Security tests. Stall observations.
1				Operational characteristics Verification of design. Special investigations.
2				Study of wind gusts. Comparison of mills. Optimization study.
3				Wind characteristics. Storing of production data. Recording of acc. stress.

Measuring programme, windmill A and B.

Figure 13



INSTRUMENTATION OF ROTOR A

Figure 14

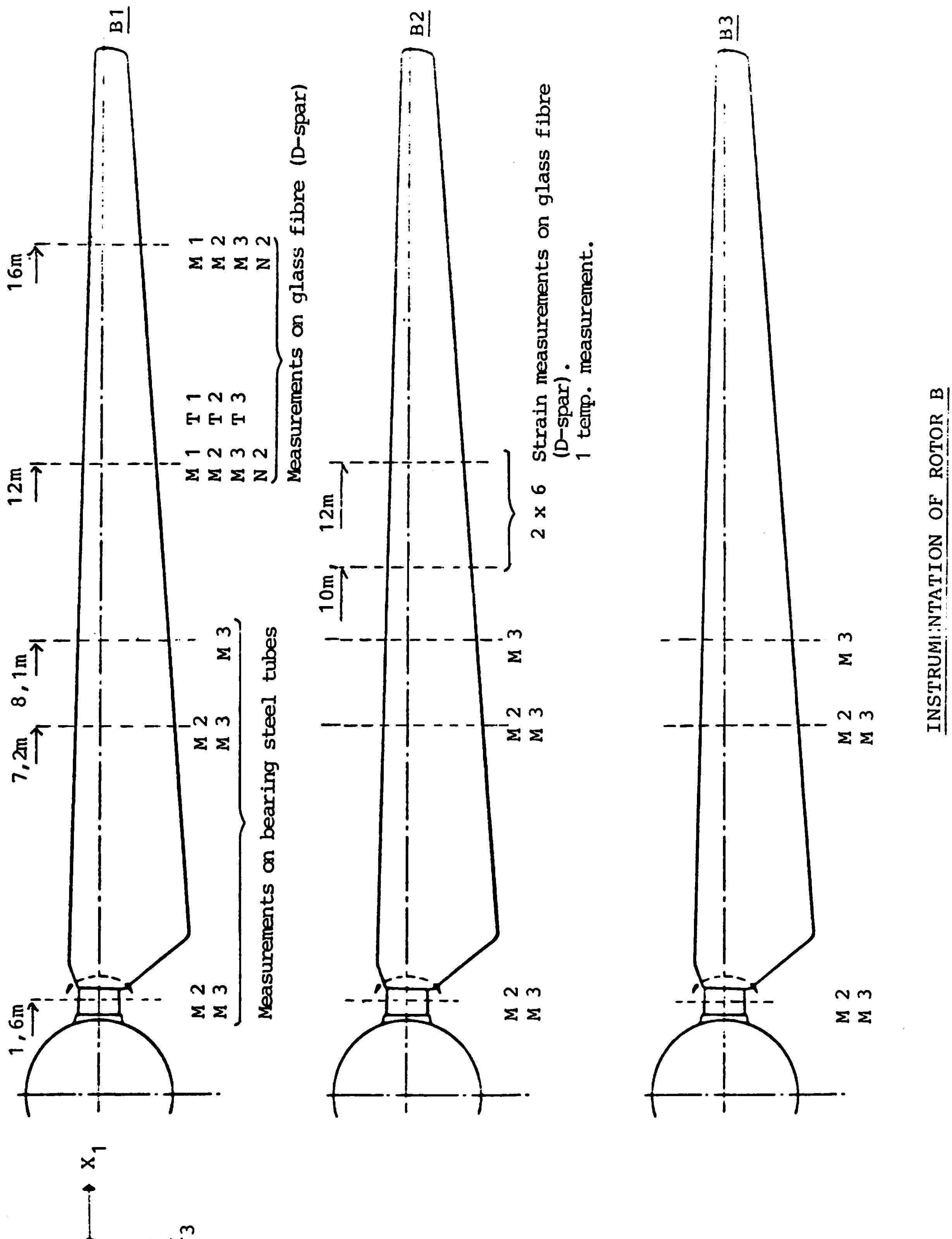
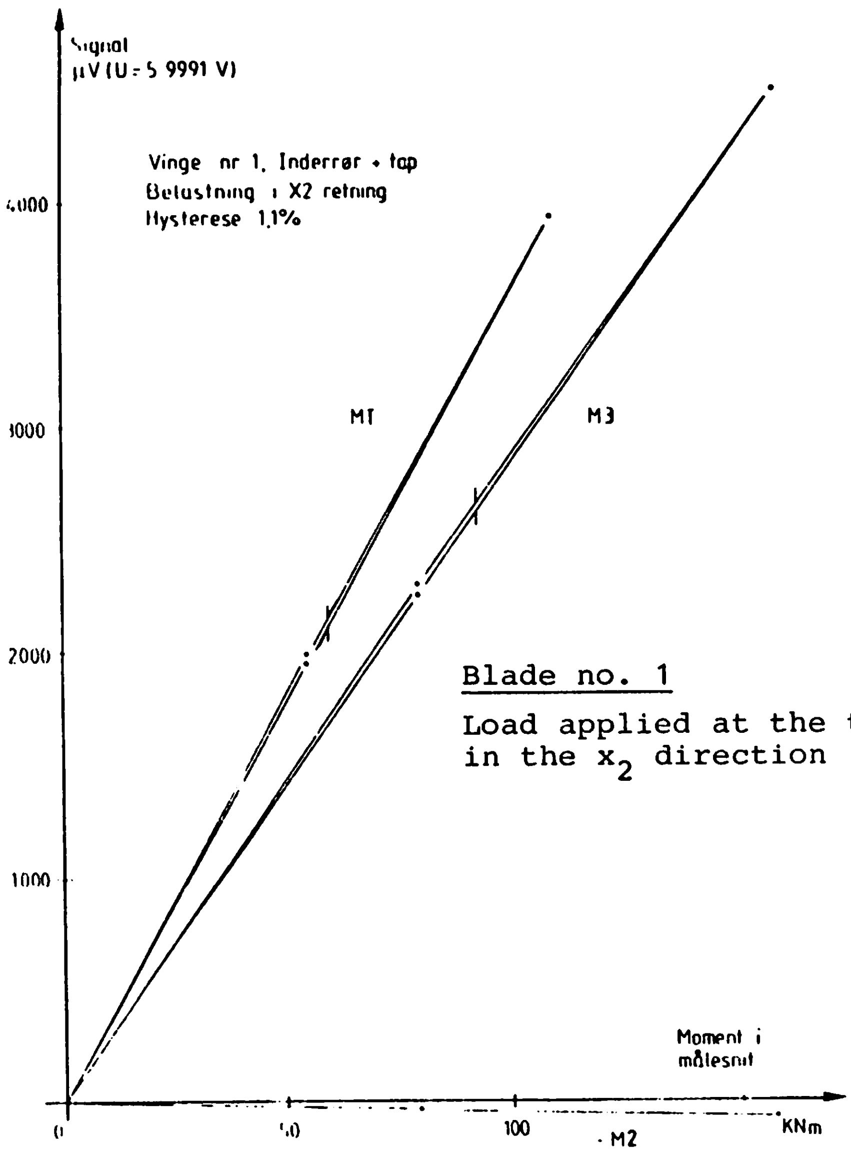

B1
B2
B3
16m
12m
8,1m
7,2m
1,6m
12m
10m
M 1 T 1 M 1
M 2 T 2 M 2
M 3 T 3 M 3
N 2 N 2
M 2
M 3
Measurements on glass fibre (D-spar)
Measurements on bearing steel tubes
2 x 6 Strain measurements on glass fibre (D-spar).
1 temp. measurement.
INSTRUMENTATION OF ROTOR B
x_1
x_2
x_3

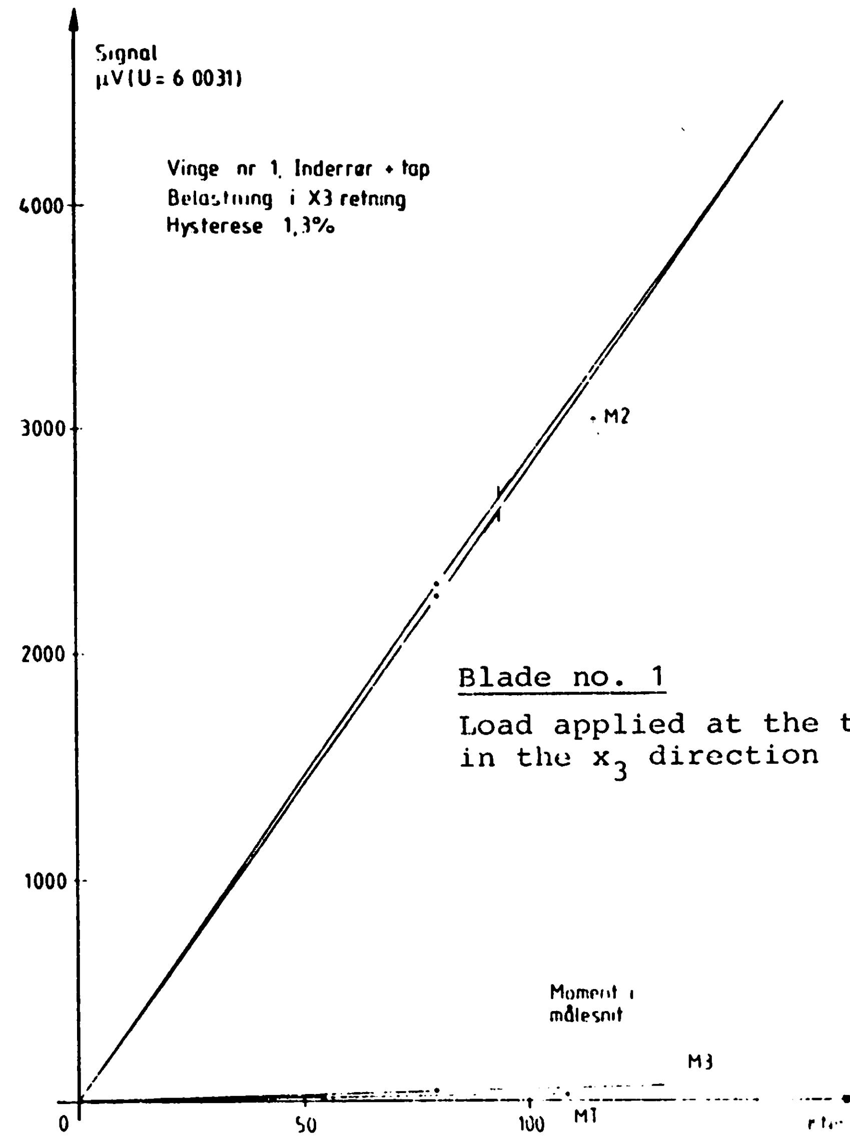
Figure 15



Blade no. 1

Load applied at the tip in the x_2 direction

Bending moments in two sections



Blade no. 1

Load applied at the tip in the x_3 direction

Bending moment in one section

Figure 16

Parameter	Sensor	Number ①	Range	Unit
Wind speed (3, 10, 25, 45, 56 m)	Cup anemometer	5	0 - 60	m/s
Wind direction (10 and 45 m)	Cos-sin resolver	4	0 - 360	°Az
Air. temperature (2 m)	Pt-100 resistor	1	-25 to + 35	°C
Diff. air temperature (10 and 56 m)	Pt-100 resistor	1	± 10	°C
Air pressure (Ground level)	Barometer	1	948 - 1083	mbar

① Number refers to number of measuring channels.

INSTRUMENTATION OF METEOROLOGICAL TOWER

Figure 17

Parameter	Sensor	Number	Range	Unit
Bending moments	Strain gauge	9 } ①	0 - 160	kNm
Normal forces (stays)	Strain gauge	9 } ①		kN
Strain (glass fibre)	Strain gauge	12		μ Str.

① 18 measuring channels available.

INSTRUMENTATION OF ROTOR A

Parameter	Sensor	Number	Range	Unit
Bending moments	Strain gauge	19 } ①		kNm
Torsional moments	Strain gauge	2 } ①		kNm
Shear forces	Strain gauge	2 } ①		kN
Temperature	Resistor	3 } ①		°C
Strain (glass fibre)	Strain gauge	12		μ Str.
Temperature (-)	Resistor	1		°C

① 25 measuring channels available.

INSTRUMENTATION OF ROTOR B

Figure 18

Parameter	Sensor	Number	Range	Unit
Rotor position	Disc on gen. shaft, 40 holes	1		DEG
Pitch angle ①	Lin. pos. transd.	1	A: -20 to +15 B: -10 to +43,5	DEG
Main shaft torque	Strain gauge	1	0 - 400	kNm
Gen. shaft torque	Strain gauge	1		kNm
Wind direction	Wind vane on nacelle	1	-180 to +180	^{o}Az
Nacelle position	Potentiometer	1	0 - 359.5	^{o}Az
Force in reg. rod	Diff. pressure	2	2x(0 - 160)	bar
Angular velocity, gen.	DC-Voltage	1	0 - 60Π	rad/s
Angular velocity, gen.	AC-Voltage	1	±3Π	rad/s
Div. temperatures	Pt-100 resistor	3		^{o}C

① 4 pos. on mill A. Continous scale on mill B.

INSTRUMENTATION OF NACELLE A/B

Figure 19

Parameter	Sensor	Number	Range	Unit
Accelerations (2 horizontal, 1 torsional acc.)	Accelerometer (Placed at top of tower) ①	3		

① Not installed. Preparations made in datasystem.

INSTRUMENTATION OF TOWER A

Parameter	Sensor	Number	Range	Unit
Accelerations (2 horizontal 1 torsional acc.)	Accelerometer ①	3		
Normal and shear forces	12 transducers between tower and nacelle ②	36		

① Not installed. Preparations made in datasystem.
② Not installed. 12 dummy plugs installed.

INSTRUMENTATION OF TOWER B

Figure 20

Parameter	Sensor	Number	Range	Unit
Current	Trafo	1	0 - 40	A
Voltage	Trafo	1	0 - 25	kV
Active power	Trafo	1	-120 to +1200	kW
Reactive power	Trafo	1	0 - 500	kVAr

INSTRUMENTATION OF GENERATOR A/B

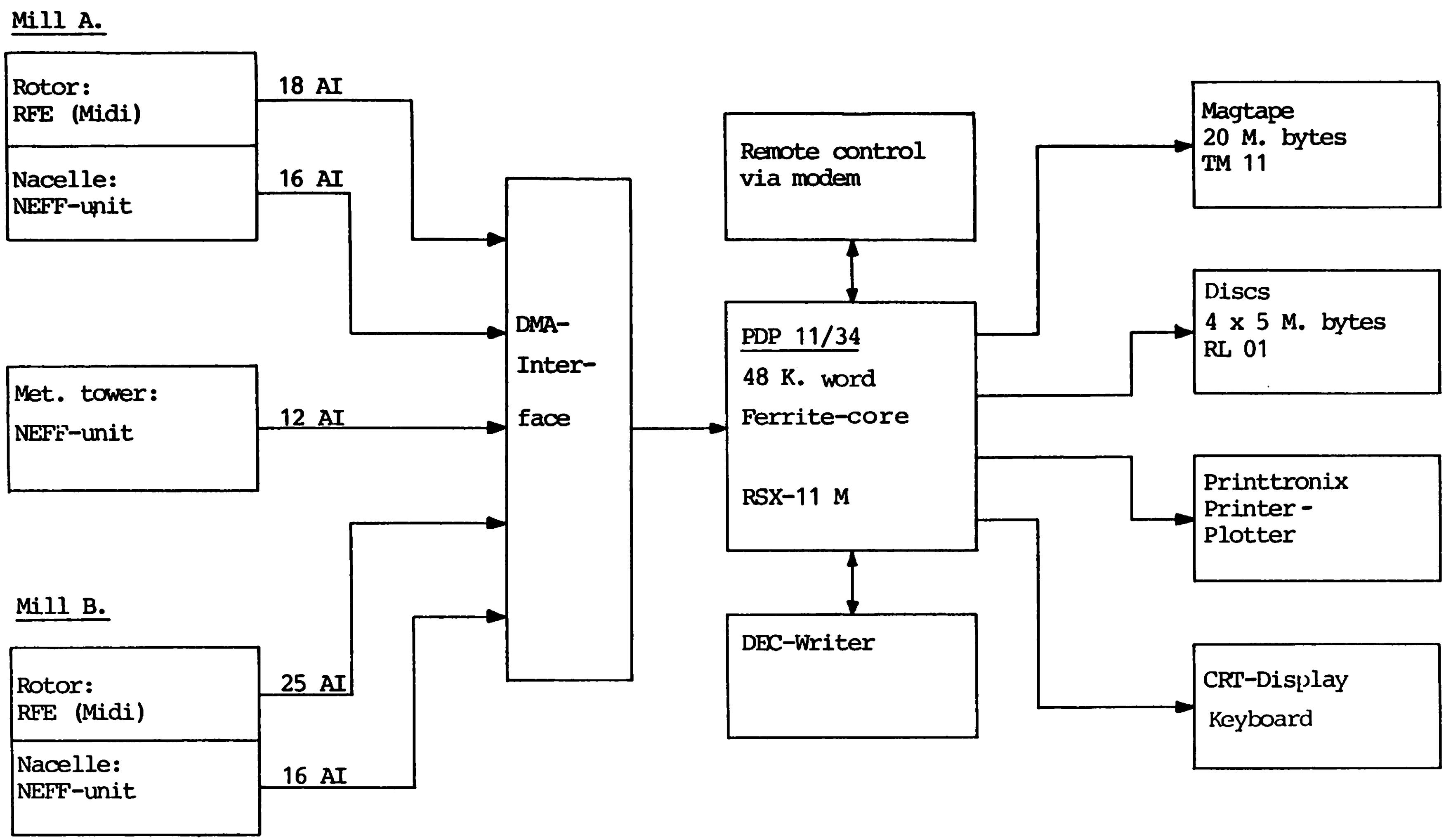
Additional instruments on each mill:

- Counter for operational hours.
- Counter for generated kWh.
- Counter for number of start-actions.
- Counter for number of yaw-actions.

Common instruments:

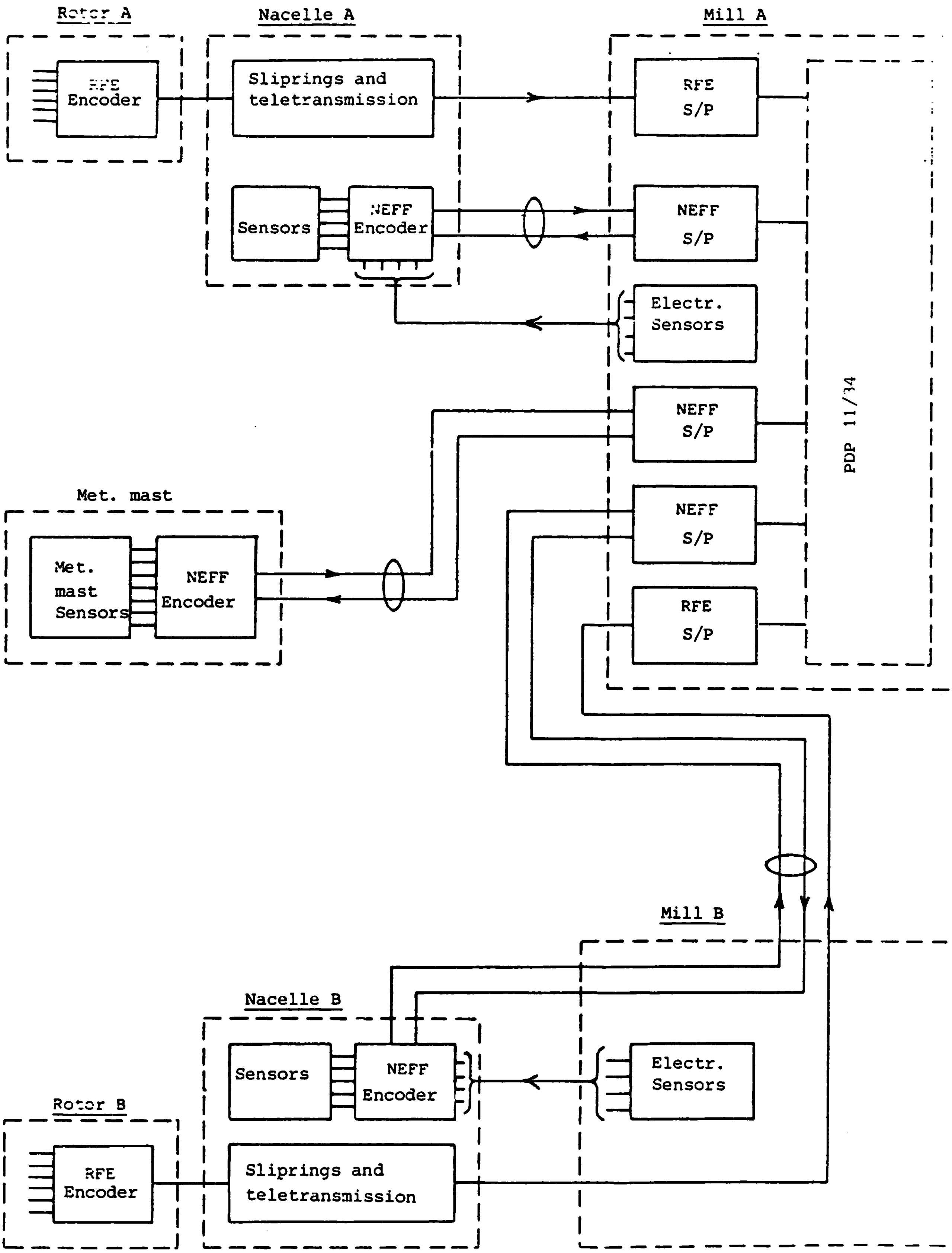
- kWh received from utility grid.
- kWh sent out to utility grid.

Figure 21



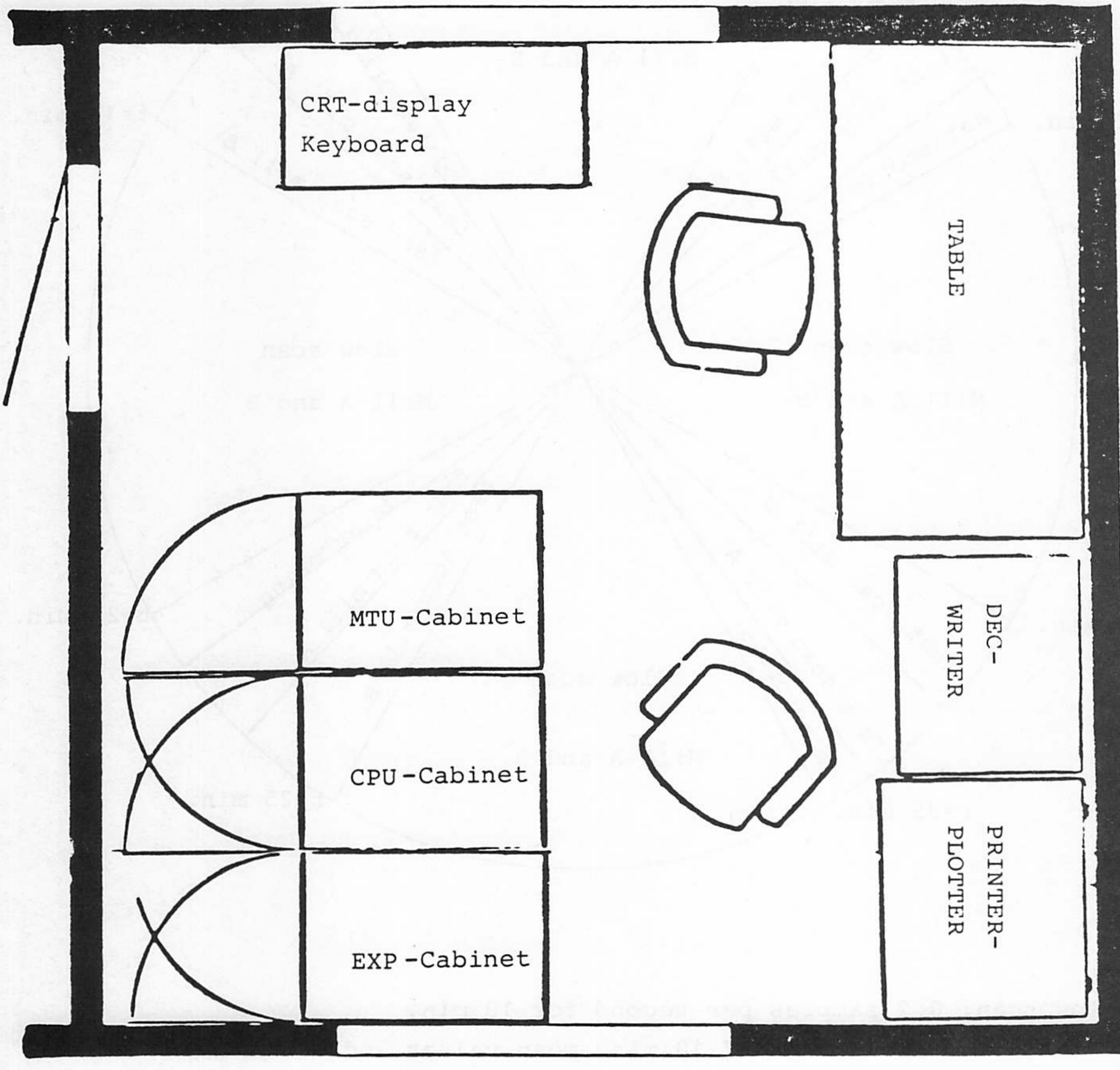
Datasystem, windmill A and B, Nibe.

Figure 22



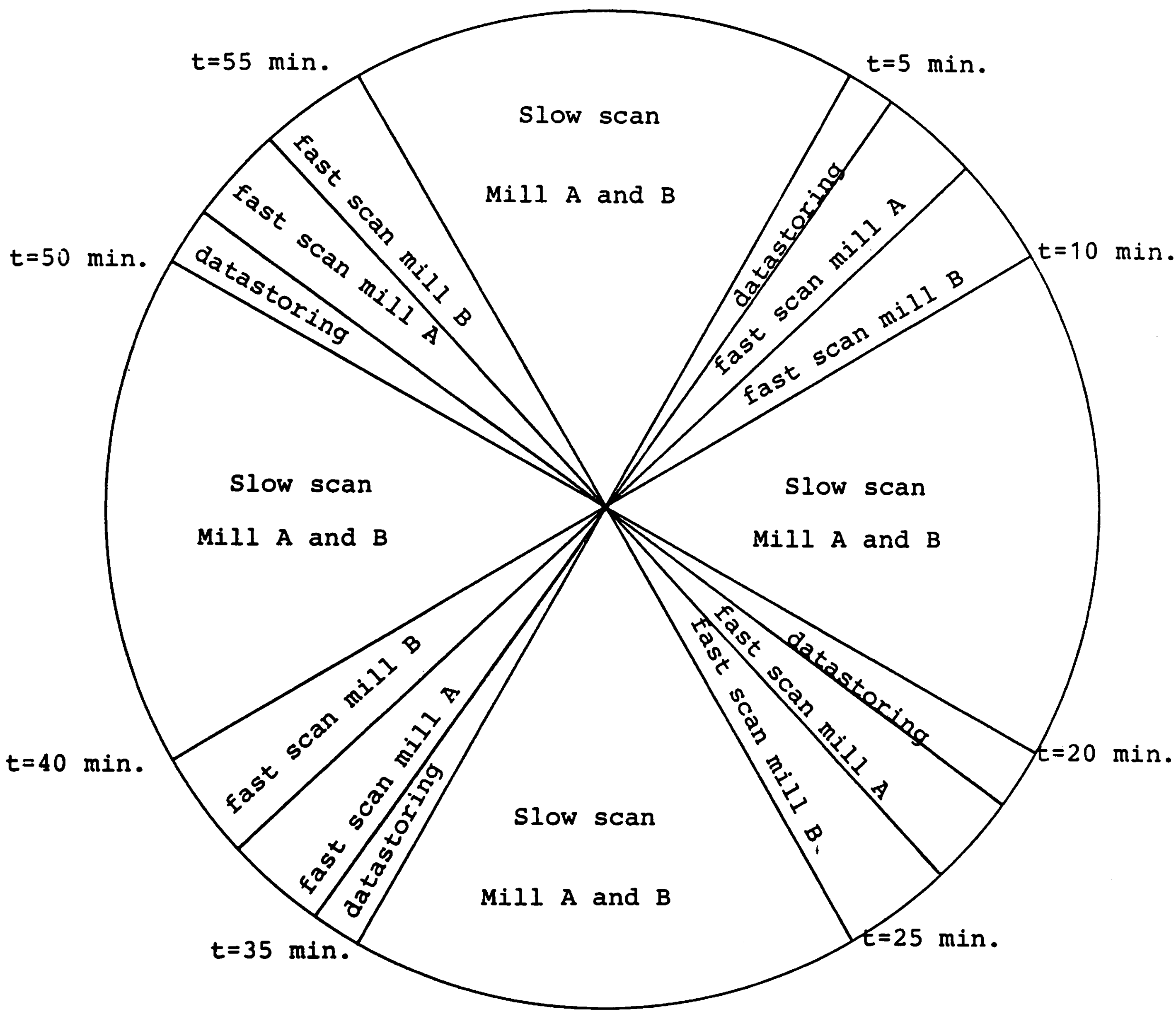
DATA ACQUISITION SYSTEM

Figure 23



Computer room, appr. 10m².

Figure 24



Slow scan: 0.2 samples per second for 10 min.
Calculation of 10 min. mean values and variances.

Fast scan: 50 samples per second for 2 min.
Calculation of resonance frequencies.

<u>Principle of data collection, stage 3.</u>

<u>Figure 25</u>

Summary of costs (excl. tax) for measuring programme for two 630 kW WECS covering the period: 1978 - 1980.

		kkr	k$
	Experiments with instrumentation and calibration of blades	221	42
	Final instrumentation and calibration of 2 x 3 blades.	535	102
	Additionel instrumentation in the nacelle.	105	20
1)	Rent of measuring system	1.955	372
	Service on measuring system	244	46
	Additional computer equipment	30	6
	Computer room	50	lo
	Measurements, stage 0	loo	19
	Measurements, stage 1 and 3	800	152
2)	Measurements, acoustic noise and electromagnetic disturbances	loo	19
	Cooperation with WECS staff members	200	38
3)	Operational costs	600	114
	Administration, management, etc.	400	76
	Total (1 d.kr. = 5,25$)	5.340	1.016

Note 1: Own property by paying additional 590 kkr

Note 2: 40 kkr from national agency of environmental protection included.

Note 3:

Utility staff	550 kkr	
Maintenance, etc	250 -	
	800 -	
Generated electricity	-200 -	
	600 kkr	

Figure 26

Measurement of Wind Conditions and Load in the GROWIAN Project x)

by

F. Körber, Maschinenfabrik Augsburg - Nürnberg AG -
Neue Technologie, Munich, Germany.

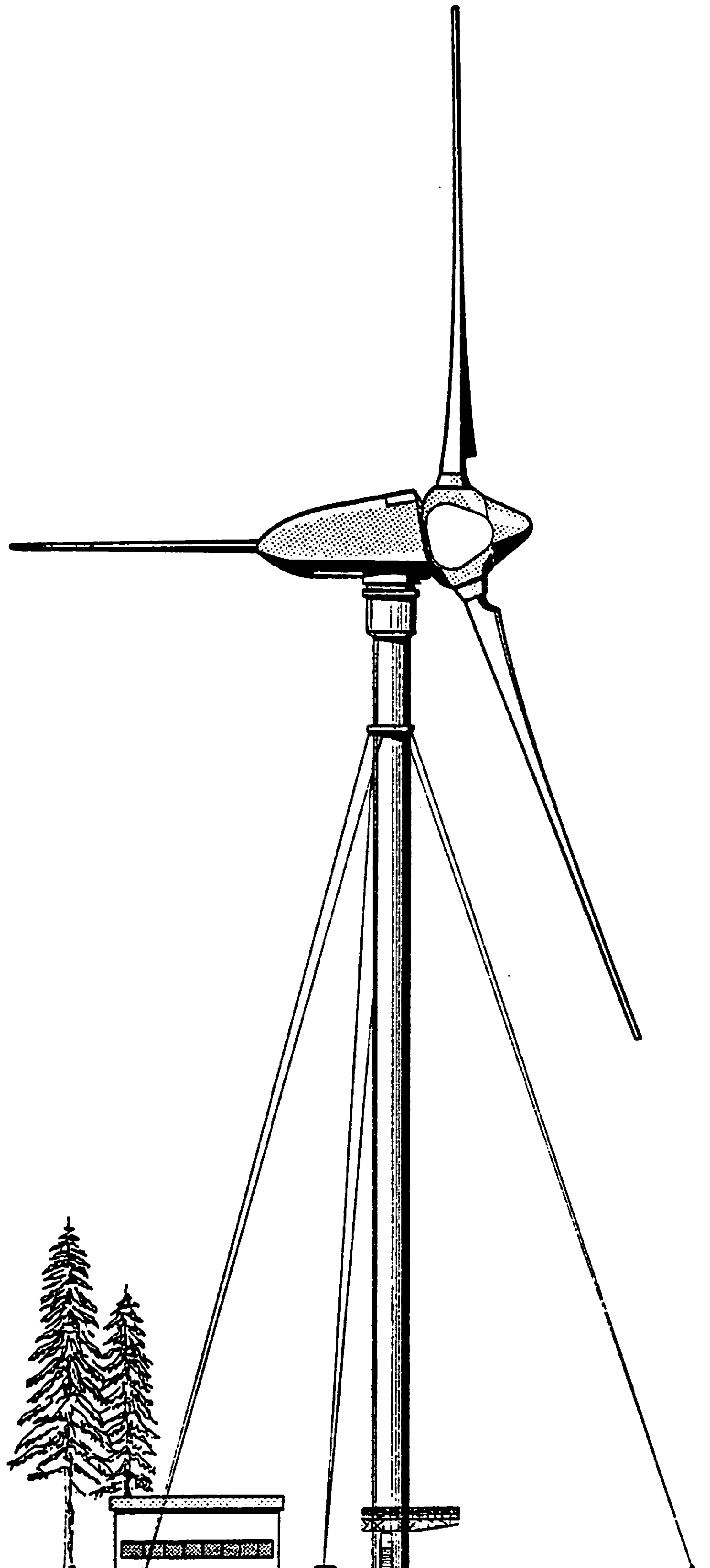
1. Summary

This report deals with planned measurements on the German wind energy converter GROWIAN which will operate in the early eighties. GROWIAN is a large scale wind machine with 100 m tower and a 100 m two-bladed rotor. Rating is 3 MW.

The report gives a survey on two themes treating wind conditions and load and stress on the machine and its components. There are as yet no experimental results available.

Wind condition will be evaluated by an arrangement consisting of three wind measuring towers 150 m, respectively 160 m high. One standing 570 m in front of GROWIAN, a pair of towers standing 70 m in front. Strain gauges, accelerometers and other equipment are used for load and stress evaluation.

x) To be presented at the IEA Expert Meeting on Data Acquisition and Analysis for Large - Scale Wind Energy Conversion Systems



Large Scale Wind Turbine
GROWIAN 3 MW

Fig. 1

2. Introduction

The project GROWIAN is one of the German wind energy activities sponsored by the Ministery of Research and Technology.

Works started in 1977 defining the construction in 1978 which is layed down in specifications and drawings. The fabrication of one test blade and two operational blades is prepared now. Construction of the other components will be ordered in fall 1979. Plans predict operation of GROWIAN in 1981.

Main data of GROWIAN are:

Performance	
- Rated capacity	3 MW
- Mean annual energy output	12 GWh
- Power-to-area ratio	380 W/m^2
Wind	
- Rated wind speed	11,8 m/s
- Cut-in speed	6,3 m/s
- Cut-out speed	24,0 m/s
Dimensions	
- Rotor diameter	100,4 m
- Rotor speed	18,5 rpm $\pm$ 15 %
- Hub height above ground	100,0 m
- Mass of nacelle with rotor	240 t

Figure 2 shows a comparison of dimension including buildings and WECs.

After the erection of GROWIAN, which we hope to finish in 1981, a test and measurement program will start which is supposed to last for 2 or 3 years. At the moment we are in the planning stage of this program.

Our test and measurement program (abbreviation MP) shows a lot of tasks to be completed:

Information on earlier works

Definition of measurement method
Transducer, data handling, data processing, data analysis

GROWIAN adaptation to measurement procedure

Planning of measurements on

- Wind conditions
- Wind turbine power
- Kinematics and dynamics
- Load and stress
- Electrical system
- Optimum operation
- Environmental impact

Provision of a mathematical GROWIAN model

Conducting measurements and analysis

For this report two themes have been chosen:

- Measurement of wind conditions
- Measurement of load and stress

3. Wind conditions

There are many unanswered questions concerning wind conditions in the field of large wind turbines. Data used today by the engineer designing a large wind machine give a somewhat rough view on the meteorologic conditions although the maximum values which are important for a WEC are known from long term statistics.

For this reason special emphasis was layed on the measurement of wind condition and the interaction of wind and machine in the GROWIAN program. This concerns local conditions as well as chronical variations. The measurement concept is based on three wind measuring towers each of which reaching the maximum blade tip height of 150 m or little more. The local arrangement of measurement towers in respect to GROWIAN is shown in Fig. 3, 4 and 5. Main wind direction at the site is WSW. Wind is blowing from free sea in a perpendicular direction to the dike. Location of GROWIAN is about 1600 m inland from the dike. The influence of the dike which is 8 m high on the wind field is negligible because of the 1000 m distance to the first measuring tower. The purpose of this first mast is to receive wind data at far upstream condition where no effect from the turbine itself on the windflow is to be assumed. The tower is a stayed truss construction made of angle iron. This is not an optimum solution because of high drag coefficient. A better construction will be used for the pair of towers standing near GROWIAN. They will also be built in truss construction but pipes which perform a much lower drag will be used. So it can be assumed that the measuring towers with their stay cables have only a negligible influence on the wind flow meeting the rotor area of the WEC. Fig. 6 shows the pair of masts.

The goal to be met by the arrangement of wind measuring towers is threefold.
One side is to be seen in measurement of wind velocity, direction, temperature and humidity in the undisturbed airflow approaching GROWIAN. This will be done by tower 1. It will have anemometers at several stations at different levels on the tower. Because of reliability conventional anemometers will be used. The data from tower 1 have long term character for wind statistics, but also can be used in a short term mode for gust measurements.

Long term and short term data from tower 1:

- Wind speed vs. height
- Wind speed duration for power calculation
- Wind direction vs. height
- Air temperature vs. height
- Air humidity
- Chronical variation of wind speed and direction vs. height (gusts)
- Vertical dimension of gusts

On the other hand the pair of towers near GROWIAN will be used for measurement of data approximately valid for the rotor area. We think that this approximation does not include too many faults although the plane of measurement is about 70 m away from the rotor plane itself. A smaller distance is not possible because of the yaw movement of the WEC's nacelle which brings the blade tips close to the meteorological towers and theit stay cables.

In fig. 5 the towers are seen in wind direction. Each one spreads 12 m long arms on both sides bearing the transducers. The plane thus defined is perpendicular to the main wind direction. The arrangement or the anemometers provides a network that is representative for the cross section of stream lines meeting the rotor. It will give us the possibility to test "what the rotor sees" and to register the response of GROWIAN. These measurements are in majority short term evaluations which will be conducted in campaigns when wind direction corresponds to the directional arrangement of towers and GROWIAN. So a disadvantage of the local arrangement of the measuring towers which might appear at first glance is not so serious. We think that in a 20 percent portion of GROWIANs operation time wind will blow from the right direction. This will be enough for the intended investigations. If the wind turns for 180° the wake of the wind turbine can be evaluated.

Data from the pair of towers 2 and 3:

- Wind speed vs. rotor area
- Wind direction vs. rotor area
- Chronical behaviour of wind speed and direction
- Response of the WEC to wind characteristics
- Dimension of gusts
- Simulation of blade rotation by timed switching on the transducers along the blade's circular movement
- Wake measurements of rotor and tower
- Definition of a representative wind measuring spot as to operation control
- Evaluation of the sequence of gusts

Finally there is a third possibility using the towers for wind investigation. On the way from tower 1 to the towers 2 and 3 the windflow will undergo changes, e.g. shape and dimensions of gusts. Maybe we can get some information about the properties and behaviour of these air formations which the meteorologists describe as cylindrical or egg-shaped. They are of special interest for the design of large rotors for they can influence it partially causing one-sided loads on the structure.

Load and stress

The wind machine has to resist loads coming from external and internal effects. As the machine is an elastic construction it will allow complicated movements. Figure 7 gives an impression of the various individual movements of the components.

In figure 8 a load flow diagram is shown. The forces acting on the different components and the whole machine are specified in quality. The list includes the following forces:

- Weight
- Centrifugal force
- Aerodynamic force
- Inertia force
- Dynamic overload
- Blade pitch adjustment force
- Yaw drive force
- Stay force
- Additional force (e. g. ice, forces from teetering)

For the measurement of these loads and the resulting strains many transducers must be installed in GROWIAN. A rough review on measuring spots, the quantity registered and the proposed sensors is given in the following table.
A graph in fig. 9 shows the situation for measurement of load and stress.

Measuring spot	Quantity measured	Sensor	Number
tower			
foot	fixing force	force transducer	8
shaft	bending/stress	strain gauge	) 120
	vibration	strain gauge	)
	acceleration	accelerometer	6
	vibration, displacement	laser beam	2
stay cables	tension	force transducer	3
	vibration	accelerometer	6
interface tower/nacelle	fixing force	strain gauge	24
nacelle	acceleration	accelerometer	3
yaw drive	yawing forces	strain gauge	6
rotor bearing	rotor shaft forces	strain gauge	12
rotor			
teetering bearing	force	strain gauge	24
hub structure	bending/ stress	strain gauge	60
blade bearing	fixing force	strain gauge	48
blades	stress	strain gauge	) 450
	vibration	strain gauge	)
		accelerometer	12
	displacement bending/ torsion	measuring beam –	
		strain gauge,	150
		laser beam	4

Measurements on the blade

GROWIAN features a blade with a nominal length of 50 m, rotor axis to tip. For the prototype a blade with a steel spar over the whole length will be used. The airfoil is built of glass fiber and fixed on the spar. Figure 10 shows a drawing of the blade. Three blades will be built in the actual program. One will undergo laboratory tests with static and dynamic loads and a final crash test. The other two are mounted on GROWIAN.

On the structure and the skin of the blades strain gauges will be applied. The blade shows fittings for holding accelerometers for measurement of accelerations at different blade radius. In the center of the spar it is planned to install a measuring beam for the determination of bending and **torsion** of the blade (fig. 11). The beam will be held in clamps which are fixed in the blade structure, so it will follow the movements of the rotor blade. Another possibility for registering the blade motions especially in the tip region is a piece of equipment that sends a laser beam from the center of the rotor to the blade tip. The swinging blade will meet the beam at different spots of its surface where a number of photocells are installed. Preparatory works in laboratory tests of the complete blade will show the usefulness of the measuring equipment planned for the wind turbine tests.

The forces acting on the blade were calculated. The maximum value in longitudial direction is 1100 kN. The force in the two other directions are lower. The maximum bending moment acting on the blade root is 10 000 kNm. Computations that take into account dynamic overload from gusts and tower wake showed that there is no danger ahead so far as we can see now.

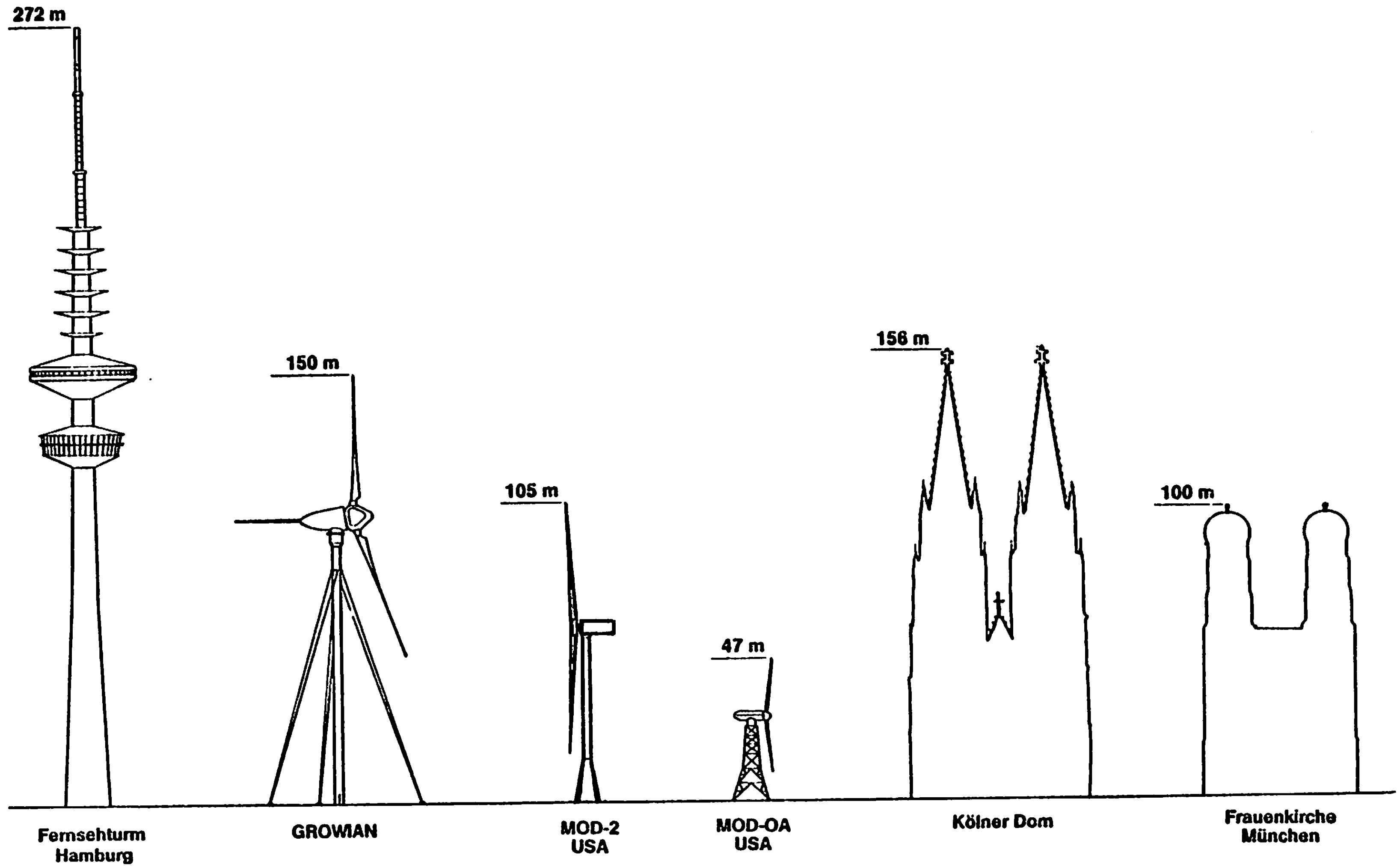
Measurement on the hub and nacelle

The next component following the blade is the teetered hub. The main part of measurements to be conducted will be the determination of strains. The frame of the teetering hub needs a number of strain gauges. The loads come from the blades and the blade pitch adjustment device. A special problem arises from additional loads occuring if the teetered hub goes to the stop at maximum amplitude. Figure 12 shows a drawing of the teetered hub.
Measurements in the nacelle (fig. 13) include accelerations and strains especially on the interface to the rotor and on the interface to the tower including yaw drive force.

Measurement on the tower

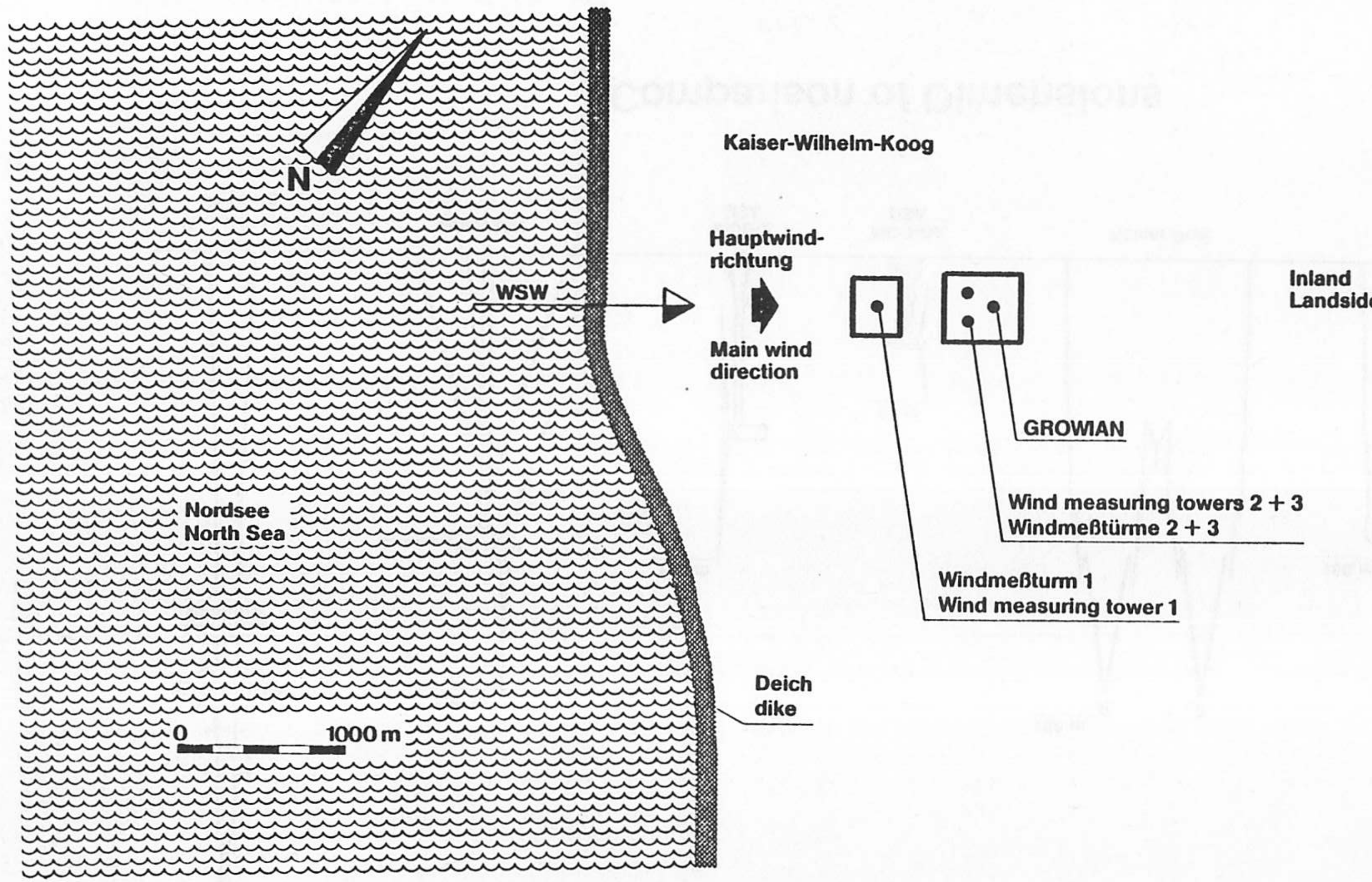
The tower will be built in steel pipe construction. Usually wind energy towers are designed for high eigenfrequencies. Against this, GROWIAN features a tower with a low eigenfrequency (fig.14). It is designed to lie between the lower rotor frequency and the higher blade passage frequency. Therefore frequency measurements are of extraordinary significance. After erection there will probably be some discrepancy between the tower eigenfrequency and the rather narrow bands where no excitation of the tower is supposed. For that reason a careful tuning of the building is necessary. The tuning will be accomplished by installing additional masses in the tower and by tightening the cables.

From this tasks the necessary measurements can be derived. There are strain gauges and accelerometers for the tower and load transducers for the tower root which is screwed to the foundation. The stay cables need load cells and accelerometers for measurement of their tension and vibration.



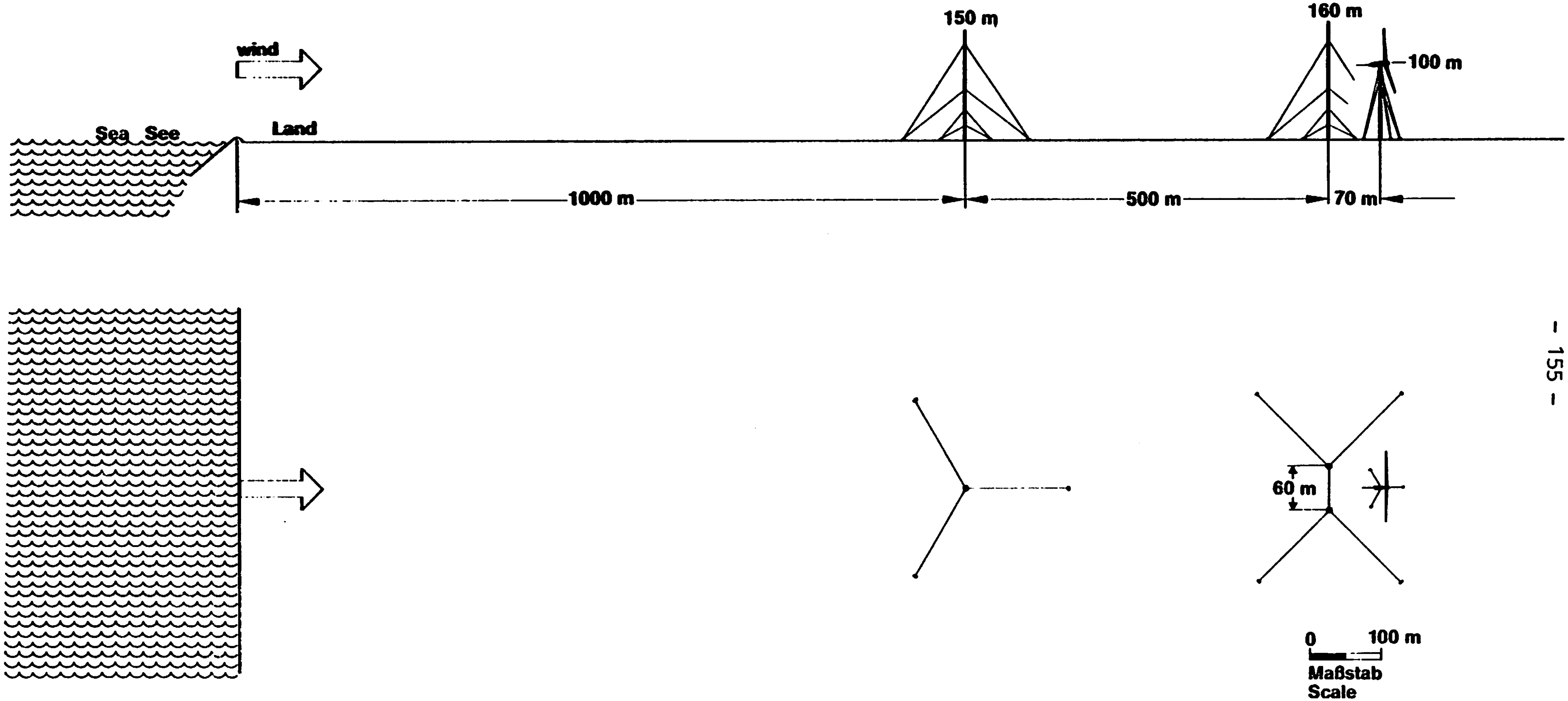
Comparison of Dimensions

Fig. 2



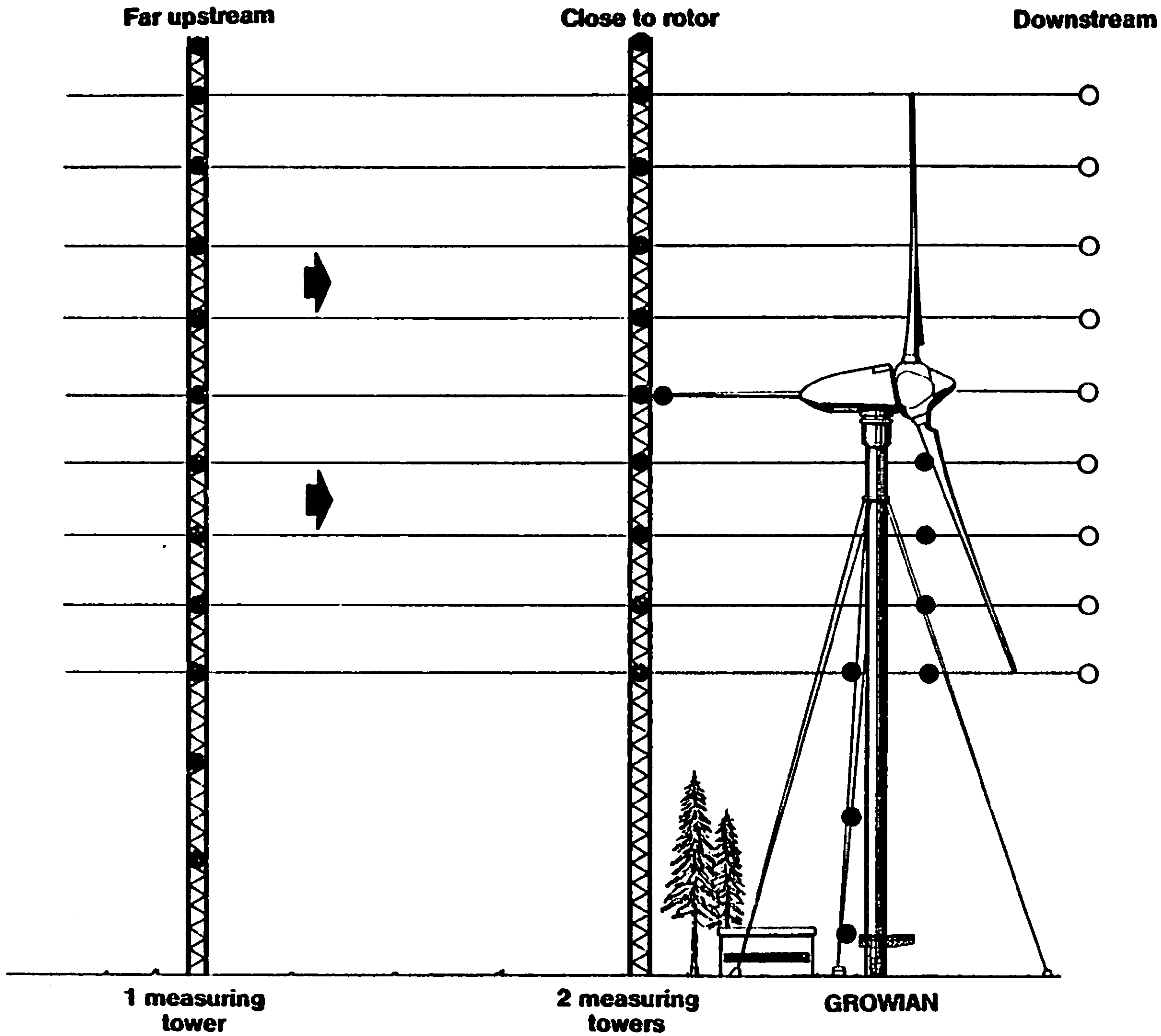
Geographische Lage
Geographic Situation

Fig. 3



Seitenansicht und Grundriß
Side view and Ground Plan

Fig. 4

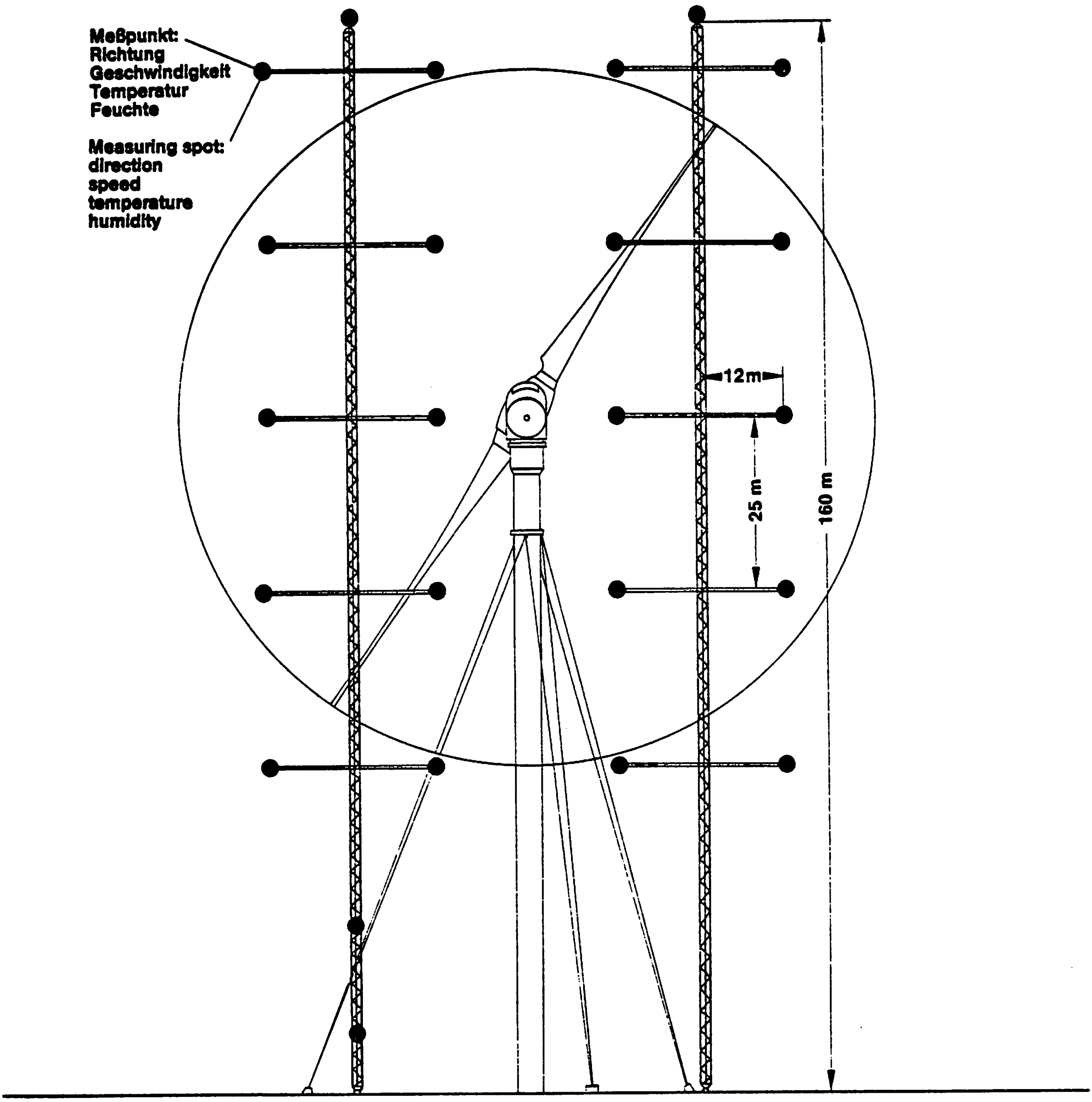


- local and chronical distribution of wind speed
- gust di-mensions and variations during lifetime of gust
- frequency of successive gusts
- wind and WEC's response
- wake of the tower
- wake of the rotor
- data for power calculation
- measuring spot representative for rotor area as to WEC control

○● Measurement spot

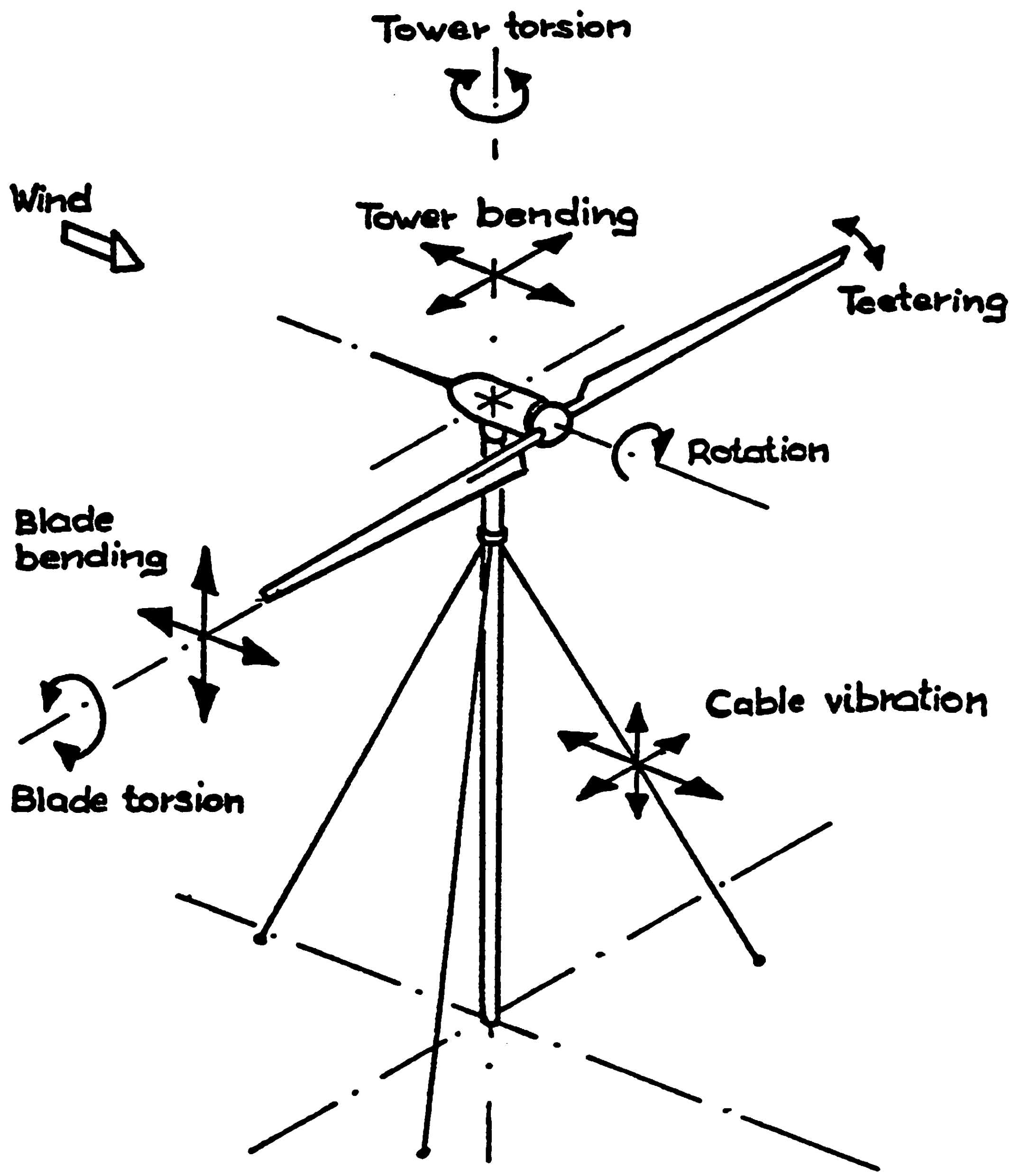
Measurement of Wind Conditions

Fig. 5



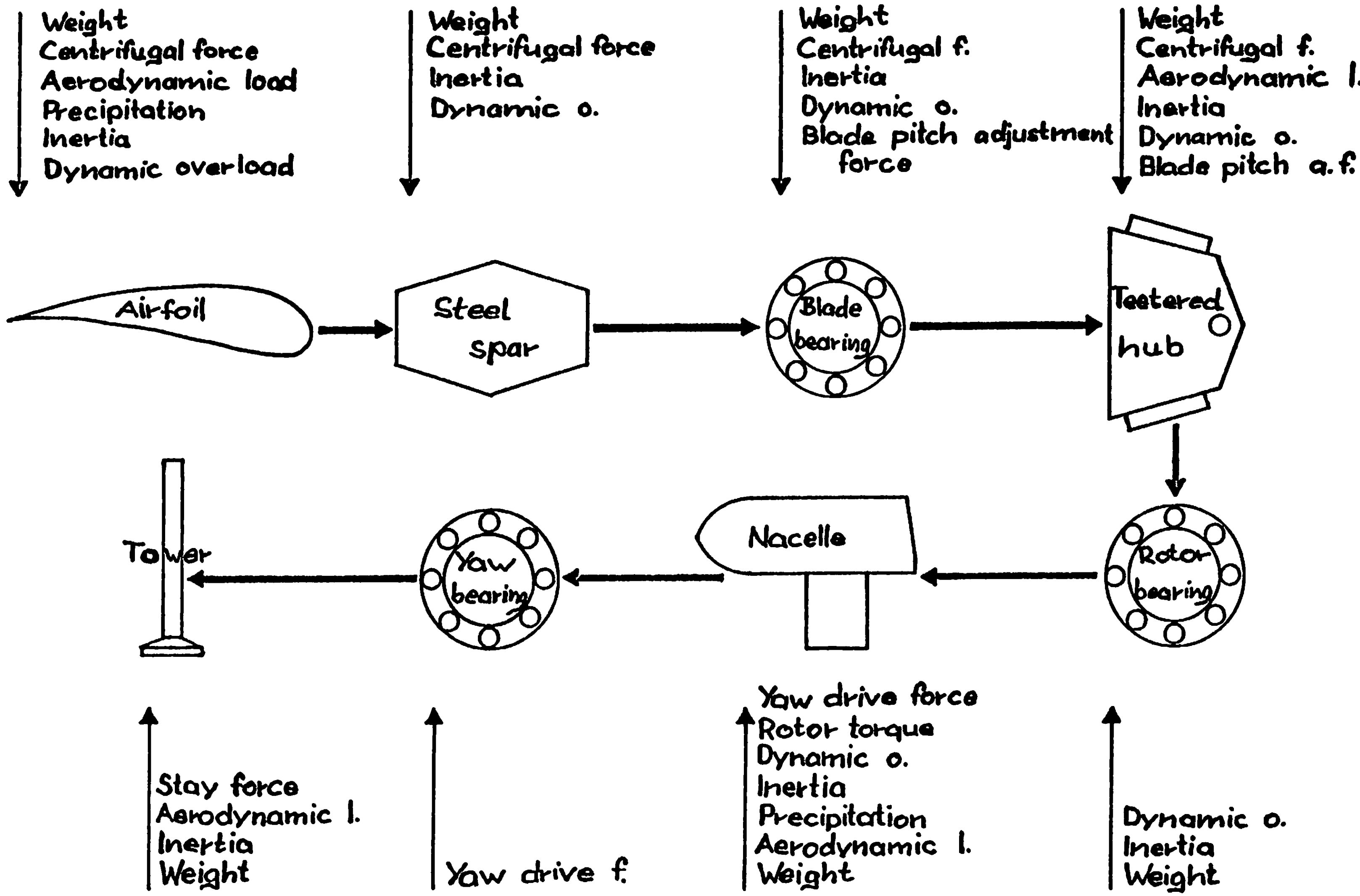
Windmeßgitter
Wind Measuring Arrangement

Fig. 6



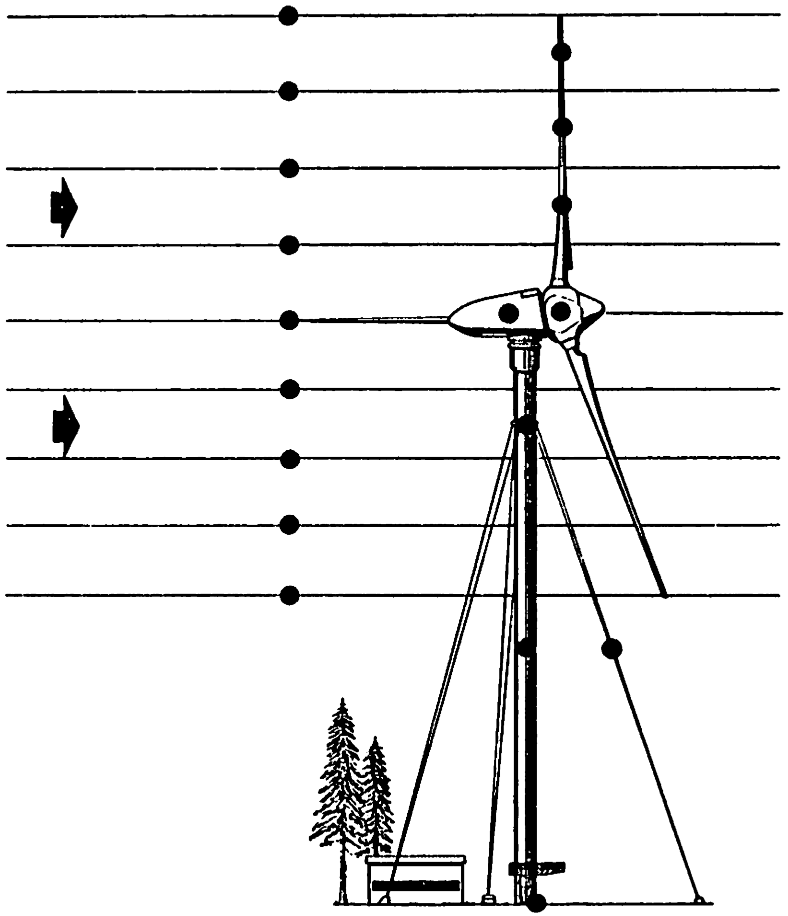
WEC Motions

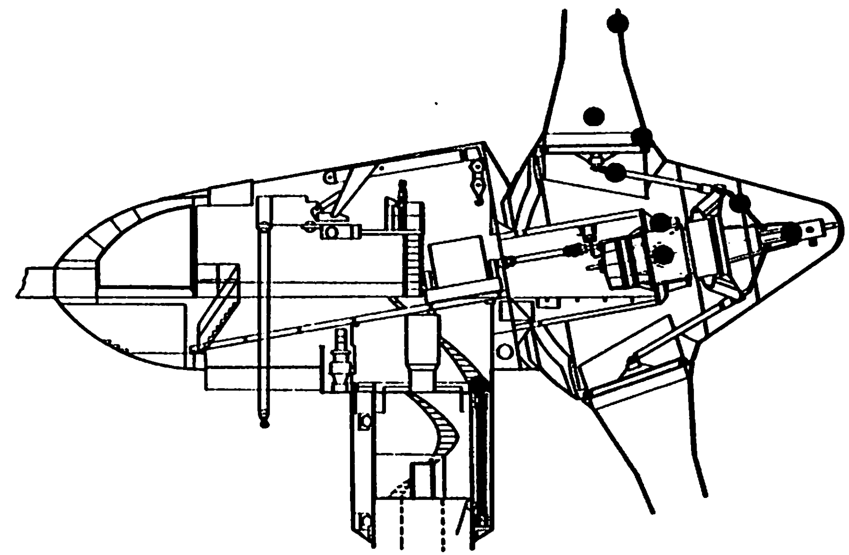
Fig. 7



Load flow diagram

Fig. 8



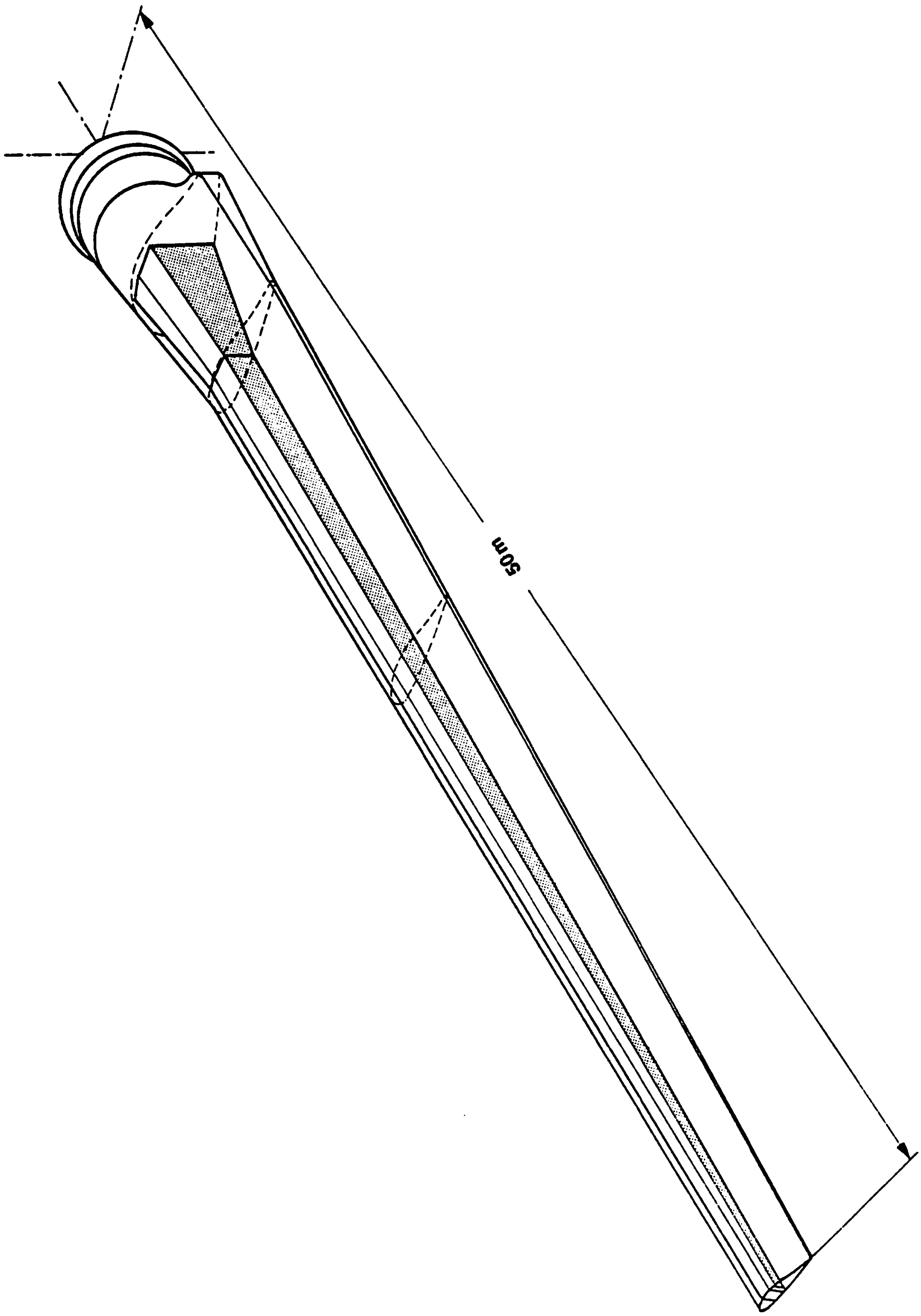


Load and stress resulting from:
- gravity
- components motion
- wind forces

acting on:
- structure
- bearings
- power drive
- adjusting and control levers

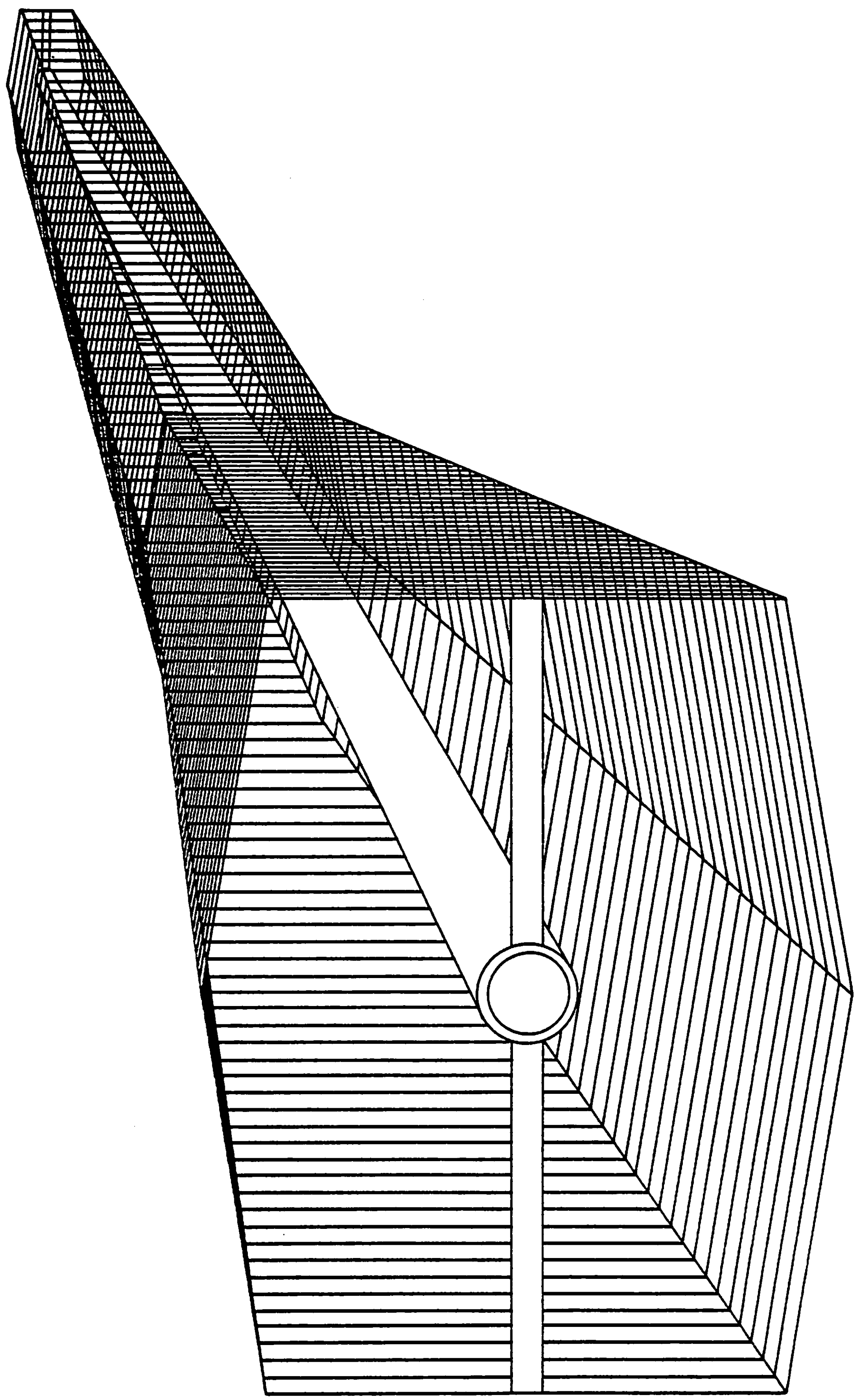
Measurement of Load and Stress

Fig. 9



GROWIAN-Rotorblade
Full steel spar version

Fig. 10



Computerzeichnung des Stahlholms mit Meßrohr
Computergraph of Steel Spar with Measuring Beam

Fig. 11

Principle of Teetered Hub

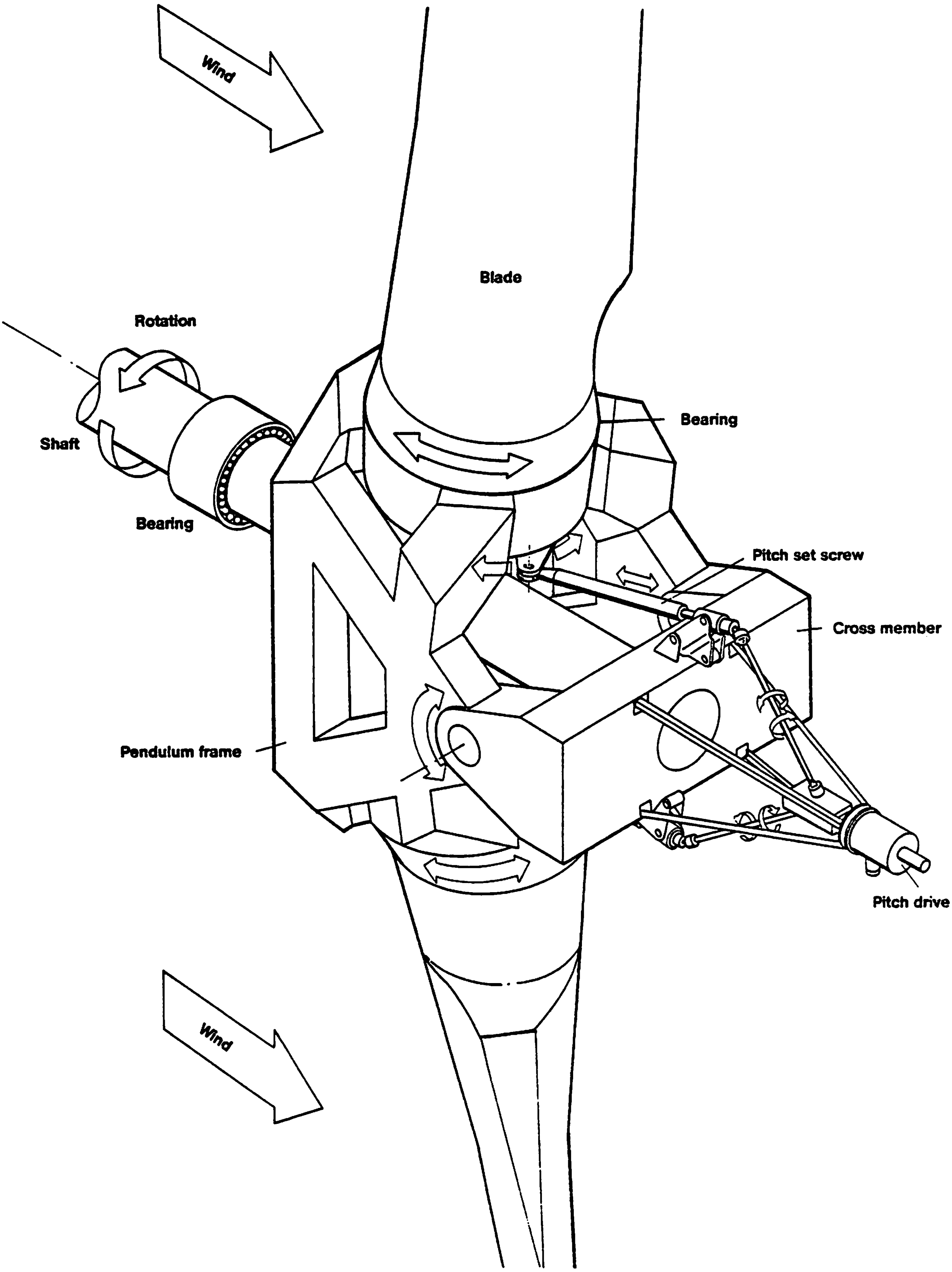
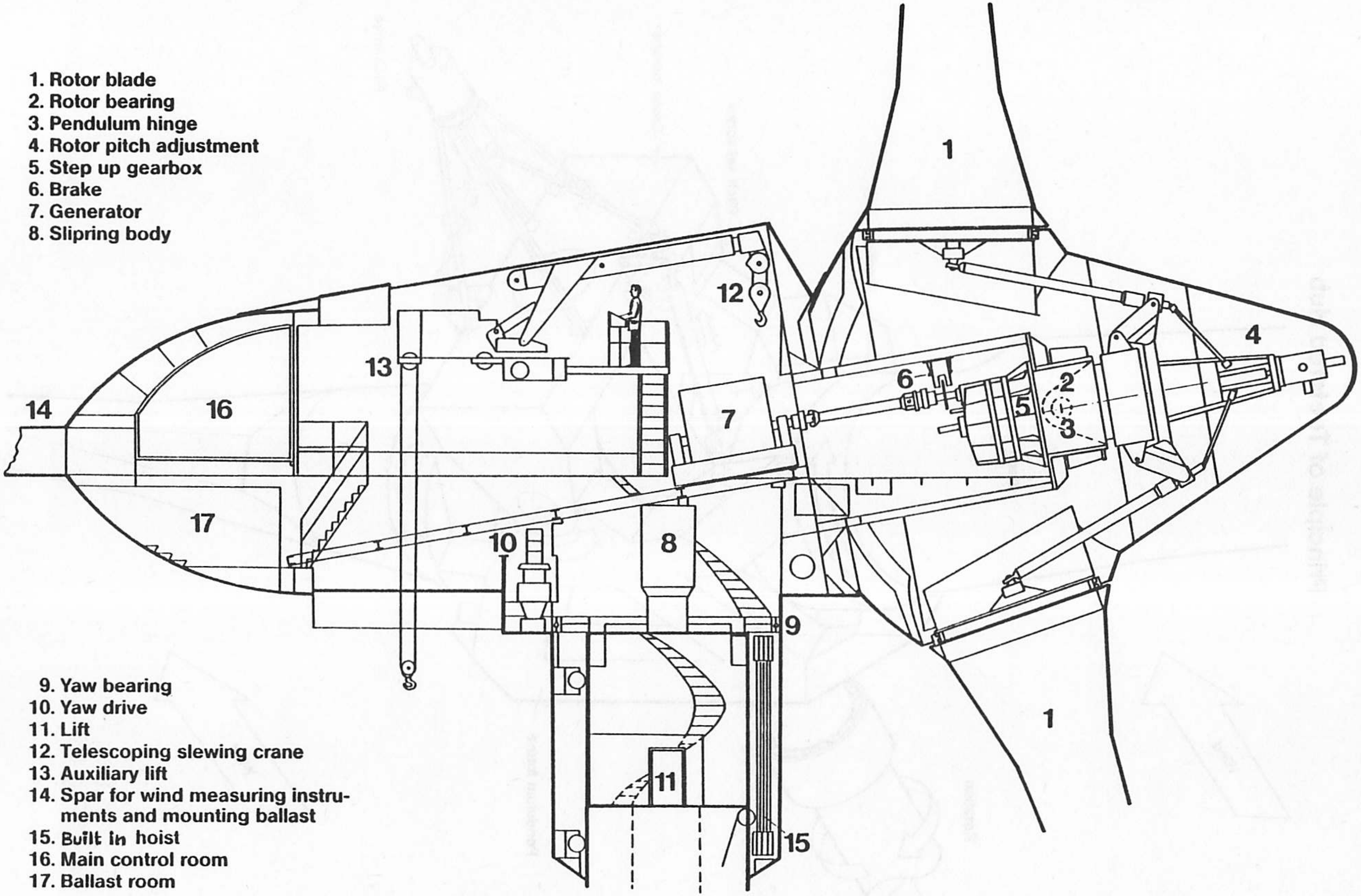


Fig. 12

Nacelle

1. Rotor blade
2. Rotor bearing
3. Pendulum hinge
4. Rotor pitch adjustment
5. Step up gearbox
6. Brake
7. Generator
8. Slipring body



9. Yaw bearing
10. Yaw drive
11. Lift
12. Telescoping slewing crane
13. Auxiliary lift
14. Spar for wind measuring instruments and mounting ballast
15. Built in hoist
16. Main control room
17. Ballast room

Fig. 13

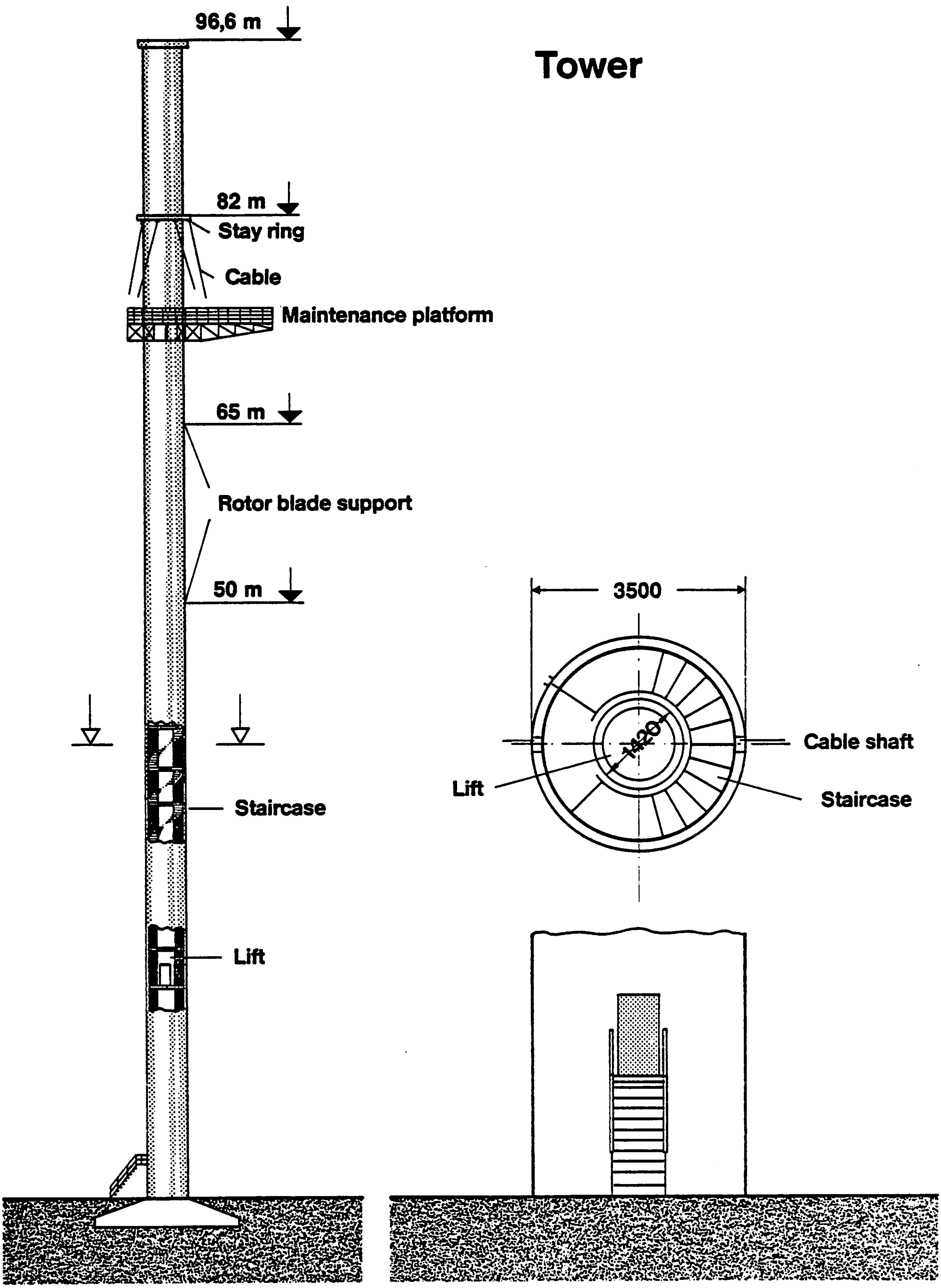

Tower
96,6 m
82 m
Stay ring
Cable
Maintenance platform
65 m
Rotor blade support
50 m
Staircase
Lift
3500
1420
Cable shaft
Lift
Staircase

Fig. 14

REVIEW OF GUST MODEL CONCEPTS[(a)]

David C. Powell

1.0 INTRODUCTION AND DEFINITIONS

Within the past two years Pacific Northwest Laboratory (PNL) has been associated directly or indirectly with several documents in which the authors set forth their concept of a wind component gust model. In this paper three models, each representing a somewhat different concept, are reviewed. The models are listed in Table 1.1.

TABLE 1.1. Gust Model Literature Reviewed

Abbreviation	Author	Title
CF	W. C. Cliff G. H. Fichtl	Wind Velocity-Change (Gust Rise) Criteria for Wind Turbine Design--PNL-2526, July 1978.
NL	D. A. Spera T. R. Richards	Wind Gust Analysis for Wind Turbine Design--memorandum from NASA Lewis Research Center, July 1978. Appended to One-Dimensional Gust Modeling for Wind Turbine Design: Literature Review and Analysis--PNL-3138, December 1979.
HF	C. H. Huang G. H. Fichtl	Gust Rise Estimates for Wind Machine Design in the Atmospheric Boundary Layer--PNL-2530, July 1979.

A gust model can be defined as a mathematical model that begins by describing wind fluctuations in terms of discrete events and ends by defining statistics of those events. In the present models, all wind fluctuation is described in terms of either individual wind components with respect to a Cartesian coordinate system at a single point, or volume averages of these wind components.

(a) This paper was based on work preformed under U.S. Department of Energy Contract No. EY-76-C-06-1830.

The models are difficult to compare as documented. They begin by defining different discrete events and end with statistics that require different descriptive words. One of the models is primarily for fatigue calculations and the others are primarily for calculating frequency of occurrence of rare gust events. Additional differences of definition are encountered in the models.

This paper describes some work we are now conducting. We have created our own basis for comparison of these models and have drafted a document, copies of which are now in the hands of the original authors. After receiving their comments, we shall publish the appropriately modified document. Using the better mix of ideas that will be available to us at the completion of the review, we plan to create new gust models, if necessary, to avoid the shortcomings of the reviewed models.

The subjects of this talk are (1) the basis of comparison and (2) the review of the three previously named gust models. In this talk the review comments, particularly the more interpretive ones, are tentative since written comments from the authors have not yet been received. Before discussion of our subjects, however, we present the definitions of turbulence and wind gusts that have been assumed in this analysis.

1.1 TURBULENCE DEFINITIONS

Turbulence describes wind component fluctuations at an observation point (x,y,z) in terms of a Cartesian coordinate system with the x-axis pointing in the direction of the mean wind, the y-axis horizontally perpendicular, and the vertical axis pointing upward.

The most basic concept in all turbulence definition is that a total fluctuating quantity can be divided conceptually into two parts--a mean and the fluctuations about that mean. Referring to the longitudinal component of turbulence (the component in the direction of the x-axis) we can write these ideas as:

$$U(t) = \overline{U} + u(t) \tag{1.1}$$

where U(t) is the total fluctuating quantity; $\overline{U}$ is its mean value; and u(t) is the fluctuating part. The mean wind is defined with respect to a period T over which the turbulence is assumed to be a stationary process. This equation is:

$$\overline{U} = \frac{1}{T} \int_0^T U(t)dt. \quad (1.2)$$

The corresponding integral of the fluctuating part u(t) is zero by definition.

Turbulence fluctuations v(t) and w(t), for the lateral and vertical directions, can be defined by an analogous set of equations for these components. The only difference is the $\overline{V}$ is zero by definition of the directional orientation of the coordinate system. Also, the expected value of $\overline{W}$ is generally zero. The remainder of the definitions are for the longitudinal component only.

A primary turbulence definition is that of the turbulence variance. This is given by:

$$\sigma_u^2 = \frac{1}{T} \int_0^T u(t)^2 dt \quad (1.3)$$

It has the dimensions of energy per unit mass.

The time function u(t) is a continuous, correlated function of time because of the eddy structure of turbulence. Therefore, the variance may be decomposed over a range of frequencies that represent a range of eddy (or fluctuation) sizes in the stream of air advected past the observation point (x,y,z) by the mean wind. The frequency function is the turbulence power spectral density function $\phi_u(n)$, where n is cyclic frequency, and is related to the variance by:

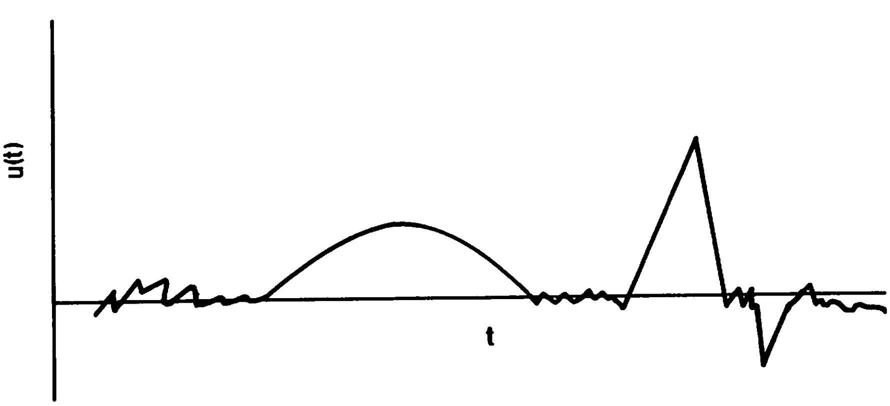
$$\sigma_u^2 = \int_0^\infty \phi_u(n)dn \quad (1.4)$$

If the concept of a turbulence power spectrum is not immediately appreciable, it may perhaps be better understood, by entertaining an analogy. The rendition of a musical composition can be considered as a time function analogous to u(t)--likewise, the grooving of a musical composition on a phonograph record. The turbulence variance is analogous to the total sound energy in the music, and the power spectrum is analogous to the distribution of this energy over sound frequencies.

However, this analogy breaks down in two ways. First, owing to the scale structure of Western music, most musical renditions favor discrete frequencies. For example, the 88 keys of the piano keyboard are each associated with a discrete frequency (and overtones). On the other hand, turbulence is a continuous function of frequency.

Second, is that music, whatever it is, is not a stationary process to the person who perceives it as music. In stationary process, all representative samples taken from it yield the same statistics. For example, if a process is stationary over time T and is analyzed by computing the statistics of all moments of segments of time length T/2 starting at various points in the first half of the interval T, the statistics of all such segments should be the same.

Furthermore, if the turbulence function u(t) contains forms that appear salient and could be described as discrete events, such as the hump and the spike in the function below:



the significance of these forms is lost in such statistics of stationary process analysis as moments and power spectra. This is true because the power spectrum and variance applying to this u(t) also apply to turbulent functions u(t) in which such event configurations are completely absent.

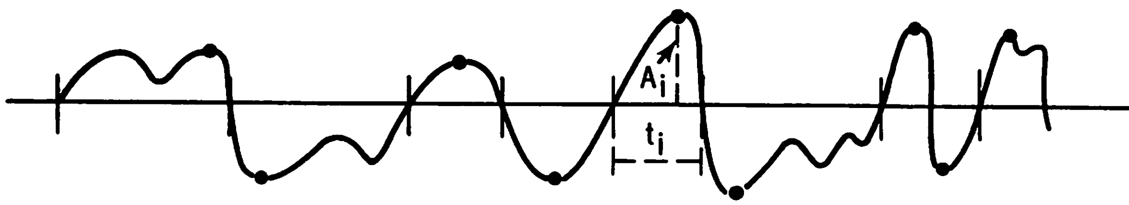
On the other hand, music is significant entirely because of the individual forms or events sensed in it, or more precisely, because of the similarity of the forms of human emotions to the forms in music.

1.2 DISCRETE GUST DEFINITION

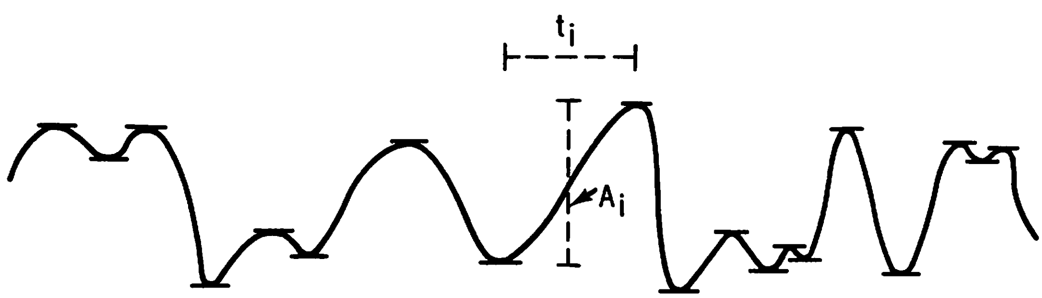
The author is aware of no technically adequate definition of gust that is uniformly accepted within the community of design engineers and atmospheric scientists involved in this literature. The definition used here will apply to a foreign body exposed to the atmosphere at a fixed location where it experiences the gust phenomena as events in time, such as an anemometer that records the passage of wind fluctuations as a time series. Within this framework we define gusts as constituting any series of discrete velocity-time events that can be defined from a turbulence time series according to some rule of utility. As indicated by the phrase velocity-time events, two independent parameters are needed to describe a gust: a measure of velocity and a measure of time duration.

Three comments should be made about the definition above before proceeding. First, this is an operational definition. The criterion, or rule of utility, depends on the usefulness of the rule with respect to some application that is extrinsic to the consideration of atmospheric phenomena. Second, this definition does not imply that discrete gusts are intermittent patches of turbulence distinguished by large fluctuations. Third, the discrete gusts are to be defined by an explicit rule. The rule could invoke a magnitude criterion such that discrete gusts under the particular definition would correspond more closely to the physical imagery the word conveys; however, this is not a necessary property. According to the definition, interesting gusts from the time series may be either intermittent or continuous.

Two examples of this type of gust definition, shown in Figure 1.1, represent a sample of wind fluctuation in the form of a wind-component time series. The discrete events are delimited by adjacent crossings of the zero value in



GUST$_0$ DEFINITION



GUST$_1$ DEFINITION

FIGURE 1.1. Definitions of Gust as a Time Series

the first series; i.e., the GUST$_0$ definition. The discrete events are delimited by adjacent crossings of the first derivative in the second series; i.e., the GUST$_1$ definition. In each case, the pair (A_i, t_i) illustrates the required measures of velocity and time increment.

Having established definitions of turbulence and discrete gusts, we now move on to discussion of the bases for comparison and descriptions of the three models.

2.0 THEORETICAL BASIS

To specify a discrete gust model we begin by defining the discrete turbulence events to which machine responses are considered significant and end by providing the mathematical means to compute the frequency of occurrence of those events, subject to necessary simplifying assumptions. The mathematical formalism is developed from the following specifications:

- one basic state of the atmosphere S that depends on mean wind speed, thermal stability, and surface roughness
- one definition of discrete turbulence events E
- one subset of events E that can be characterized by magnitude x
- one machine filter function F.

We can write the basic mathematical structure of a wind fluctuation model as:

$$N_x(S,E,F) = N_o(S,E,F)\ P[x|\sigma_E(\sigma(S,F),F)] \qquad (2.1)$$

where N_x is the frequency of occurrence of the events of magnitude x; N_o is the basic frequency-of-occurrence factor (which will be called the basic frequency factor hereafter); and P is the dimensionless probability that a given turbulence event will have magnitude x. P is a conditional probability; it expresses the probability that x will occur, given that the turbulence events E have a characteristic magnitude (rms) of σ_E. σ_E is numerically and conceptually distinct from the turbulence rms $\sigma(S,F)$, but depends on the turbulence rms as well as on the filter F. Effectively, the turbulence rms is the square root of the variance of the time series that represents the turbulence.

The x stands for a range of numbers, say all events of definition E but of magnitude larger than a given number. The physical significance of N_o, which varies from one model to another, will be discussed later. Here we simply point out that N_o is the factor on the right that gives N_x its dimension, which is that of inverse time. If the frequency of these events is to be considered as a function of all atmospheric states, then equation (2.1) must be integrated in principle as follows:

$$N_x(E,F) = \int_S N_x(S,E,F)\ p(S)dS. \qquad (2.2)$$

where p(S) is a probability density function of any atmospheric state S.

The treatment of these specifications in the three models is described in the next section.

3.0 MODEL REVIEW

The different aspects of the models are reviewed in the following order (1) data and discrete event definition, (2) spectral filtering, (3) basic frequency factor, and (4) final products. The review closes with an interpretive section.

3.1 DATA AND DISCRETE EVENT DEFINITIONS

The HF and CF models are both based on the idea that velocity change over an arbitrary interval of time is important. The data used in these models are defined by:

$$\Delta u(t,\tau) = u(t + \tau) - u(t) \tag{3.1}$$

The discrete events defined by these models make critically different use of the differencing interval as shown in Figure 3.1. The discrete events of the CF model are discrete values of the continuous process $\Delta u(t, \tau)$ separated by the differencing interval τ. These are the heavy dots in Figure 3.1. Note the double role τ plays in this definition. Not only is τ the differencing interval, as defined by equation (3.1), but it also serves as the discretization interval between successive elements of the $\Delta u(t, \tau)$ data. The discretization interval can be arbitrarily short regardless of the value of τ. The difference may be appreciated from the fact that differencing the data according to equation (3.1) arbitrarily makes τ a highpass filter parameter, while the discretization interval is essentially a lowpass filter parameter.

To create discrete events for the HF model it is necessary to draw a horizontal line at level x through the time function $\Delta u(t, \tau)$ such that $\Delta u(t, \tau)$ forms positive slope crossings with respect to the level x. These events are indicated by the arrows in the figure.

The final events in the CF model also require the line x for definition. They are the large dots at a level exceeding x. (None are shown in Figure 3.1).

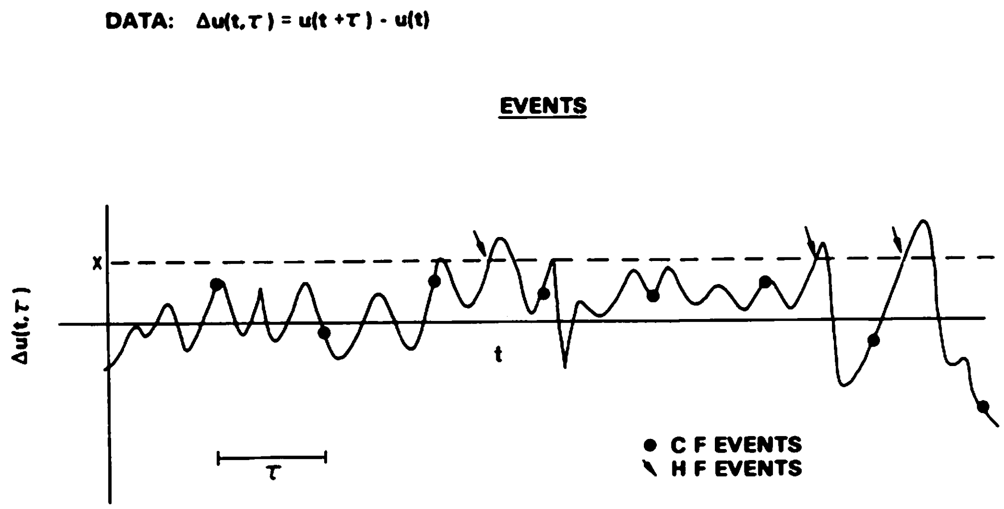


FIGURE 3.1. Discrete Events Defined (Cliff-Fichtl and Huang-Fichtl Models)

The NL discrete events are similar to those of the $GUST_0$ definition in that they are amplitudes pertaining to u(t) rather than to $\Delta u(t, \tau)$. However, the NL discrete events are idealized "one-minus-cosine" positive and negative gusts about a mean wind value. We interpret this definition as shown in Figure 3.2. The T is the most probable period of a gust of amplitude A, subject to the constraint that the inverse of T be within the band of frequency sensitivity of the machine.

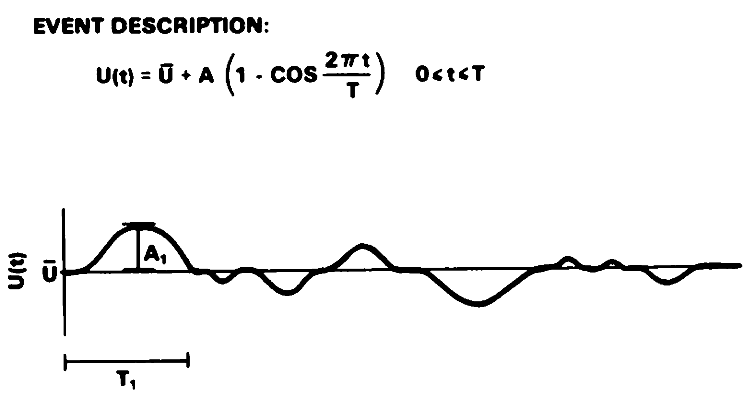


FIGURE 3.2. Discrete Events Defined (NASA-Lewis Model)

3.2 SPECTRAL EQUATIONS AND SPECTRAL FILTERING

All three models use a filtered power spectrum

$$\phi_F(n) = \phi(n)F(n) \tag{3.2}$$

where n is cyclical frequency; $\phi(n)$ is a model turbulence power spectrum ($\text{length}^2\ \text{time}^{-1}$); F(n) is a dimensionless filter; and the quantity on the left is the filtered power spectrum, that is, the power spectrum of turbulence as seen by a machine such as a wind turbine with filter properties represented by F(n).

The CF and HF models use a gradual filter that is a function of the diameter D of the disk of blade rotation. This is given by:

$$F(n) = \frac{1}{1 + \left(\frac{nD}{\overline{U}}\right)^2} \tag{3.3}$$

The half-power point of this filter is at the frequency $\overline{U}/D$. We can enlarge the filtering concept as it applies in these models by considering the differencing of the original time series according to equation (3.1) as part of the filtering. The spectrum of the differenced filtered data is related to the spectrum of the original undifferenced data by:

$$\phi_F(n,\tau) = \frac{2(1-\cos 2\pi n\tau)}{1 + \left(\frac{nD}{\overline{U}}\right)^2}\,\phi(n) \tag{3.4}$$

The NL model uses a sharp cut-off filter for computing the turbulence rms of its filtering data. Effectively,

$$F(n) = \begin{cases} 1 & n_1 \leq n \leq n_2 \\ 0 & \text{otherwise} \end{cases} \tag{3.5}$$

This filter is used to compute $\sigma(F)$, the rms of the filtered turbulence data according to:

$$\sigma(F) = \left[\int_{n_1}^{n_2} \phi(n)\ dn\right]^{\frac{1}{2}} \tag{3.6}$$

Also the definition of the constraint on the most probable time of a gust T becomes:

$$2n_1 \leq \frac{1}{T/_2} \leq 2n_2 \tag{3.7}$$

3.3 BASIC FREQUENCY FACTOR

The differences of basic frequency factor among the three models are very significant. This is the quantity indicated by N_0 in equation (2.1). Only the HF model uses a basic frequency factor that incorporates atmospheric turbulence behavior. Assuming that the turbulence is Gaussian, N_0 can be calculated using the theory of Rice (1945) according to:

$$N_0(\tau;F) = [\sigma(\tau;F)]^{-1}\left[\int_0^{\infty} n^2\phi_F(n,\tau)dn\right]^{\frac{1}{2}} \tag{3.8}$$

N_0, σ, and ϕ_f (n) are also functions of $\overline{U}/z$.

The CF model uses:

$$N_0 = \frac{1}{2\tau} \tag{3.9}$$

A comparison between these two basic frequency factors is shown in Figure 3.3. As τ becomes large (subject to a set of input data), N_0 from equation (3.9) approaches zero, whereas N_0 from equation (3.8) oscillates about the value of $N_0(F)$, the frequency of zero crossings of the undifferenced series u(t) as seen through the filter F. This is given by:

$$N_0(F) = [\sigma(F)]^{-1} \int_0^\infty n^2 \phi_F(n) dn \quad (3.10)$$

No basic frequency factor appears in the NL model. The designers use the blade rotation rate for a basic frequency factor when applying the model. (Powell and Connell 1980).

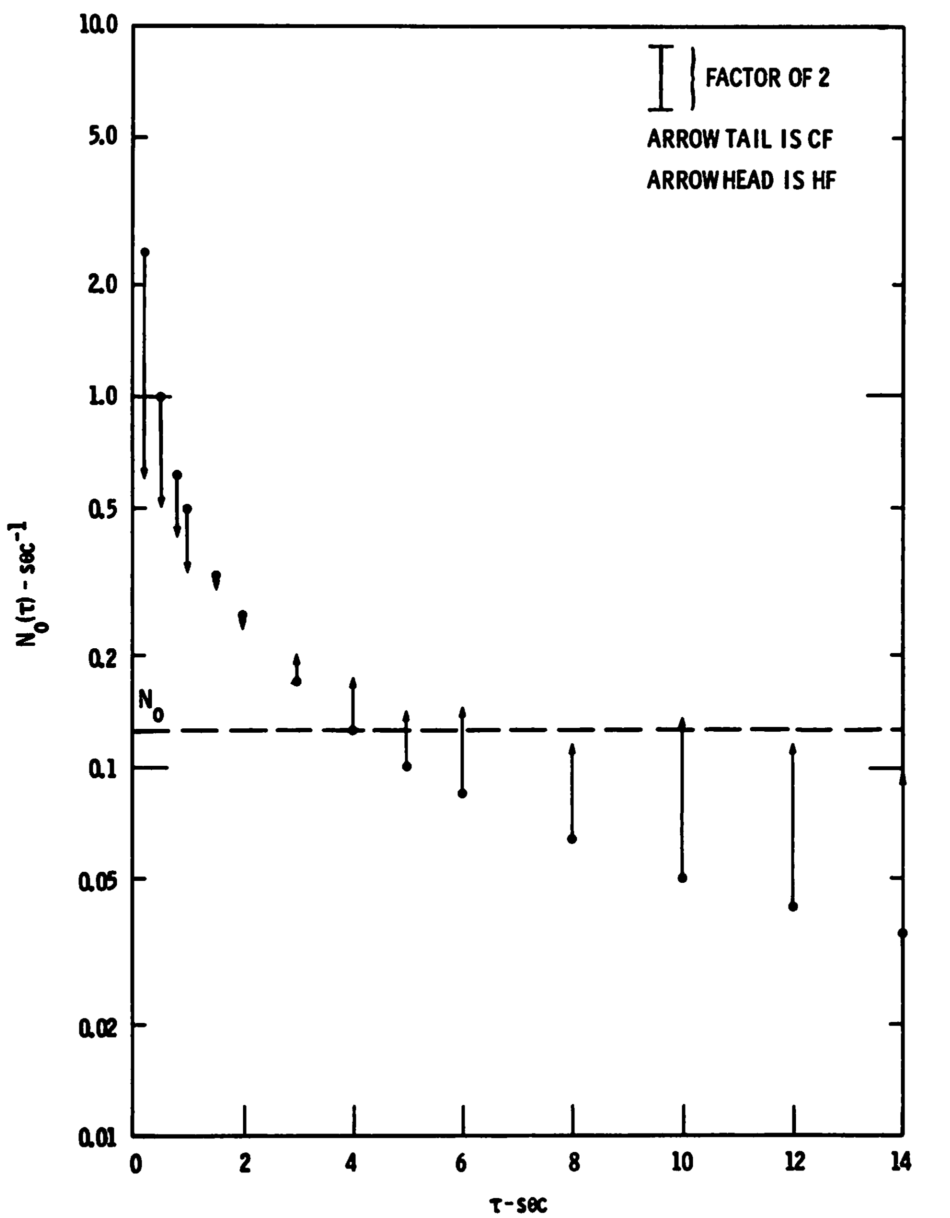


FIGURE 3.3. N_0 (τ) in Huang-Fichtl and Cliff-Fichtl Models

3.4 FINAL CALCULATED PARAMETERS

The CF and HF models both yield frequency of occurrence expressions for the velocity differences $\Delta u(t,\tau)$; see equation (3.1). The final CF expression may be written:

$$N_x(\tau;F) = \frac{1}{2\tau} \int_{\overline{U}_1}^{\overline{U}_2} \left[\frac{1}{\sqrt{\pi/2}\,\sigma(\tau;F)} \int_0^x e^{-\frac{1}{2}\left[\frac{\Delta u(\tau)}{\sigma(\tau;F)}\right]^2} d\Delta u \right] p(\overline{U})d\overline{U} \qquad (3.11)$$

$\overline{U}_1$ and $\overline{U}_2$ encompass a sufficient range of mean wind speed to account for all desired contributions. They may be machine cut-in and cut-out speeds, respectively.

$N_x(\tau;F)$ is the frequency of occurrence of positive velocity differences $\Delta u(t,\tau)$ exceeding x, subject to the following conditions and assumptions:

- The Δu data are of Gaussian probability.
- The $\sigma(\tau;F)$ reflects the machine filtering.
- The only atmospheric variable that $\sigma(\tau;F)$ is a function of is mean wind speed $\overline{U}$; otherwise, the final integration would be over $p(\sigma(\tau;F))d\sigma(\tau;F)$ rather than $p(\overline{U})d\overline{U}$. Equations are given for computing $\sigma(\tau;F)$ knowing $\overline{U}$ and F.
- The effective frequency of occurrence N_x may be computed by considering discrete values of $\Delta u(t,\tau)$ at the interval τ. Effectively, this filters out contributions from all fluctuations in $\Delta u(t,\tau)$ with frequencies higher than $1/2\tau$.

The final HF expression may be written:

$$N_x(\tau;F) = \int_{\overline{U}_1}^{\overline{U}_2} N_o(\tau;F)\, e^{-\frac{1}{2}\left[\frac{x}{\sigma(\tau;F)}\right]^2} p(\overline{U})d\overline{U} \qquad (3.12)$$

As explained before, $N_0(\tau;F)$ and $\sigma(\tau;F)$ are also functions of $\overline{U}$. $N_x(\tau;F)$ is the frequency of crossings by the $\Delta u(t;\tau)$ process of level x with positive slope. $N_0(\tau;F)$ is the frequency of zero-crossings with positive slope by the same process. The first three conditions and assumptions listed under the CF model apply here, too. The fourth condition does not apply to the HF model. (In the theoretical part of the HF model document, atmospheric stability is also considered. However, stability is dropped later when calculations are performed).

The final expression of the NL model is not frequency of occurrence, but the probability density of the amplitudes A of one-minus-cosine waves (see Figure 3.2). The final expression is:

$$p(A) = \frac{1}{\sqrt{2\pi}\sigma(F)} e^{-\frac{1}{2}\left[\frac{A}{\sigma(F)}\right]^2} \tag{3.13}$$

where $\sigma(F)$ is the rms of the u(t) process with spectrum $\phi(n)$ and is filtered according to equation (3.5).

Another difference between the equations in the NL memorandum and the documentation of the other two models is that the NL memorandum does not mention integration over the states of the atmosphere. The omission of this step is logical when the model is used in conjunction with fatigue loads that are a function of mean wind speed. However, the CF and HF documents also have equations for $N_x(\tau;U;F)$ that can be used in the same way since $\overline{U}$ moves into the argument list on the left side of the equation, and no integration over $p(\overline{U})$ occurs on the right side. These correspond to equations (3.11) and (3.12), respectively and are:

Cliff-Fichtl Model:

$$N_x(\tau;\overline{U},F) = \frac{1}{2\tau}\left[\frac{1}{\sqrt{\pi/2}\sigma(\tau;F)} \int_0^x e^{-\frac{1}{2}\left[\frac{\Delta u(\tau)}{\sigma(\tau;F)}\right]^2} d\Delta u\right] \tag{3.14}$$

Huang-Fichtl Model:

$$N_x(\tau;\overline{U},F) = N_o(\tau;F)\ e^{-\frac{1}{2}\left[\frac{\Delta u(\tau)}{\sigma(\tau;F)}\right]^2} \qquad (3.15)$$

As previously explained, the dependency on $\overline{U}$ is in $\sigma(\tau;F)$ and in $N_o(\tau;F)$.

3.5 INTERPRETATION

3.5.1 The Huang-Fichtl Model

Using the HF model the following information can, in principle, be calculated:

- frequency with which the time series $\Delta u(t,\tau)$ exceeds any designated value (frequency of level crossings at that value)
- fraction of time over which the Δu exceeds any given value
- average duration of an exceedance interval for any level x.

Only the first of these is given explictly in the document; see equation (3.12). But one may deduce from the same equation that the fraction of time R_x over which the time series exceeds a given positive value x is:

$$R_x(\tau;F) = \int_{\overline{U}_1}^{\overline{U}_2} \frac{1}{\sqrt{2\pi}\ \sigma(\tau;F)} \left[\int_x^{\infty} e^{-\frac{1}{2}\left[\frac{\Delta u}{\sigma(\tau;F)}\right]^2} d\Delta u\right] p(\overline{U})d\overline{U} \qquad (3.16)$$

Then the average duration D_x of each exceedance interval is:

$$D_x(\tau;F) = \frac{R_x}{N_x} \qquad (3.17)$$

We have two reservations regarding the HF model. First, the essential data, the net difference of u(t) over an interval τ, may not be monotonic. Non-monotonic change is as illustrated in Figure 3.4.

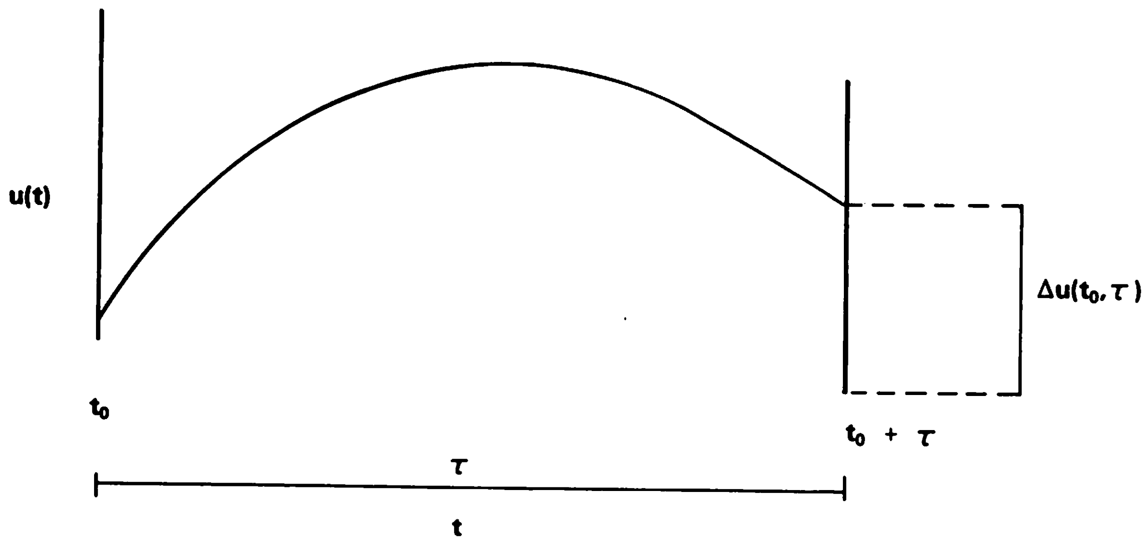


FIGURE 3.4. $\Delta u(t,\tau)$ from Non-monotonic Change in u(t)

Let us assume that this wind is filtered so that it is as "seen" by the machine. We believe that the severity of the wind effect in this interval will be underestimated if the value of $\Delta u(t,\tau)$ defined by the figure is used rather than the maximum difference occurring in this interval. If so, then a gust model defining discrete gust events only over intervals of monotonic change of u(t) should be a more conservative model.

The second reservation is with regard to the calculated frequency of occurrence of gusts of unusual magnitude, say the maximum expected gust value during the lifetime of a machine, which may be 30 years. The problem here involves the tails of model probability distributions--Gaussian for the turbulence and Rayleigh for the mean wind. The Rayleigh distribution is given by:

$$p(\overline{U}) = \frac{\pi\overline{U}}{2\overline{U}_c^2}\exp\left[-\frac{\pi}{4}\left(\frac{\overline{U}}{\overline{U}c}\right)^2\right] \qquad (3.18)$$

The calculated values of N_x are so sensitive to errors in $p(\overline{U})$ that the only realistic way to use to equation (3.12) with respect to rare gust values is to solve it inversely. That is, having a value of N_x, solve for x. This can be done by iterating the direct solution until the desired value of N_x is converged upon. Also, it is of the highest importance to have the best possible representation of $p(\overline{U})$ for a given location, particularly if the wind is calm over a significant fraction of the time. This may require a tabular, rather than an analytical, representation of $p(\overline{U})$. Of course, the assumption that turbulence at extremely high mean wind speeds can be represented by the same stationary process spectrum as applies to more usual wind speeds is questionable.

3.5.2 Cliff-Fichtl Model

We believe that the treatment of frequency of occurrence in the Huang-Fichtl model is correct in principle, and that the CF treatment is in error. The basic reason is the initial definition of data discretized at the interval τ, as shown in Figure 3.1. This either filters out or aliases (represents the contribution at a lower false frequency) all contribution to the $\Delta u(t,\tau)$ process from frequencies greater than $1/2\tau$. If our view is correct, the Cliff-Fichtl model yields only the second of the three items listed as available from the Huang-Fichtl model at the beginning of Section 3.5.1. But, ignoring this objection and assuming that the data defined by the dots in Figure 3.1 are what you want, the subsequent mathematical treatment is correct under the Gaussian assumption.

3.5.3 The NASA-Lewis Model

Only the NL model projects the idea of a discrete gust definition consistent with that given at the beginning of this paper; i.e., two parameters, amplitude and time, are intrinsically specified for each gust. It is the only model to use a power spectrum that has the correct slope at high frequencies. (Kaimal 1973).

$$\frac{n\phi(n)}{\sigma^2} = \frac{0.164(f/f_0)}{1 + 0.164(f/f_0)^{\frac{5}{3}}} \tag{3.19}$$

where

$$f = nz/\overline{U}.$$

To adopt this spectrum to neutral conditions, Frost, et al. (1978) recommend the value of f_0 = 0.0144 for the u-component.

The NL model also recognizes the need for more careful specification of the mean wind distribution, using the Weibull distribution:

$$p(\overline{U}) = \frac{k\overline{U}^{k-1}}{C^k} \exp -\left[\frac{\overline{U}}{C}\right]^k \tag{3.20}$$

where C and k are determined by curve fitting with respect to a given data sample. The Rayleigh distribution, given by equation (3.18) is a special case of the Weibull distribution.

Our reservations regarding the NL model can best be illustrated if we list their equations in an order different from their order of appearance in the NL memorandum. First we begin with the atmospheric boundary layer power spectrum, equation (3.19), and define a turbulence rms as in equation (3.6).

$$\sigma(F) = \left[\int_{n_1}^{n_2} n\phi(n)d[Ln(n)]\right]^{\frac{1}{2}}$$

We next introduce a velocity A by the probability expression, equation (3.13):

$$p(A) = \frac{1}{\sqrt{2\pi}\sigma(F)} e^{-\frac{1}{2}\left[\frac{A}{\sigma(F)}\right]^2}$$

Since turbulence is approximately Gaussian, and since the sigma used is that for filtered turbulence, we may say that A has essentially the same probability distribution as that which applies to the entire turbulence process u(t) filtered by the bandpass limits n_1 and n_2.

The turbulence of the wind is assumed to consist of a set of discrete gusts with Gaussian random amplitudes but with specified (deterministic) shapes and periods. The assumed shape of each discrete gust is as follows:

$$U(t) = \overline{U} + A\left[1 - \cos\left(\frac{2\pi t}{T}\right)\right] \quad o \leq t \leq T \tag{3.21}$$

in which t is time, A is gust velocity, and T is gust period (see Figure 3.3 for our interpretation). From equations (3.6) and (3.13) we get the impression that A is equivalent to the entire filtered turbulence process. But from equation (3.21) the A's appear to be a subset of values that define the maximum departure from the mean wind in each discrete gust event. It is not obvious that those two versions of A have the same probability density.

The other reservation we have stems from the use of blade rotation rate as a basic frequency factor, and the blade rotation time as a gust time scale in place of the intrinsic time scale T in equation (3.21). We have not attempted to show what bias results from this treatment. But at this time we suggest that if wind shear is considered to be the dominating fatigue factor, then use of blade rotation rate for a basic frequency factor appears desirable. However, if turbulence is considered to be the dominating fatigue factor, then the basic frequency factor should in some way reflect frequencies of turbulence as seen by the machine.

At this point mention should also be made of the fact that the "time scale" of a gust as seen by a machine is heavily dependent upon machine factors, much more so than is the amplitude of the gust. This determination was made from both $GUST_0$ and $GUST_1$ analysis in which the time scale of these gusts was exhibited as a markedly changing function of filtering, as the same turbulence data were subjected to different filterings in successive analyses. This work is fully described in the forthcoming review document referenced earlier.

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Correlation of wind velocity and power output from field measurements on wind turbines.

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Abstract

A brief account is given of the problems involved in getting pertinent aerodynamic and aerodynamically derived characteristics of wind turbines from field measurements.

In particular the methods for determining the proper power versus wind-speed correlation are reviewed.

Presented at the IEA expert meeting for large scale wind energy conversion systems, Boone, N.C., USA, Sept. 26-27, 1979.

1. An operating wind turbine is a complex mechanical/electrical system operating in a non-stationary environment. Hence calculations of operating characteristics are difficult, and the task of verifying calculated characteristics by measurements in the field is not an easy one.

   Matters are complicated even further by the fact, that many of the underlying assumptions in the different methods developed for handling similar situations are not met with.

2. The wind velocity and the air density (and temperature) are inputs to the system. Leaving density and temperature out as quasistationary quantities, we are left with the three components of the wind velocity, which varies with the spatial coordinates and with time in a random manner.

   The description of the properties of the wind velocity can be carried out in different domains, viz. in the amplitude, time or in the frequency domain.

   Operating in the frequency domain furnishes the most powerfull tools for handling the problems of determining the response of the elements of the wind turbine to the fluctuating inputs from the wind. Many excellent treatises on this subject exist, and a few of them are listed here as references [1, 2, 3, 4].

   Under the assumptions that

   - the system responds linearly to a random input
   - the random process is stationary, weakly ergodic with a Gaussian probability density distribution for speed

   the results of the analysis can be stated in form more or less similar to the following

$$S_{iy}(f) = \sum_{j=1}^{N} H_j(f)\, S_{ij}(f) \qquad (1)$$

   where $S_{iy}(f)$ is the cross spectral density function between the output and one of the inputs x_i, $S_{ij}(f)$ is the cross spectral density between inputs x_i and x_j and $H_j(f)$ is the system transfer function. The result stated is for the general case of correlated inputs [1]. The characteristics for every output in question (a movement of a particular point of the structure, a moment in the blade at a particular place, the driving torque, etc.) can thus in principle be determined for a given input, once a transfer function has been established.

If one wants to determine the transfer function experimentally, either because it cannot be derived through the basic equations of motion, or because we want to check the validity of a calculated transfer function, then measurements of the spectral densities are required.

3. The power output from a wind turbine is of course a quantity of prime interest. Under certain simplifying assumptions it is possible from aerodynamic theory to calculate the shaft power for the case of steady wind [5,6].
The effects of wind shear and tower shadow can be accounted for in the calculations, quasisteady aerodynamics being assumed.

This static power curve now turns out to be non-linear, (fig.1), which means a.o. that one of the assumptions necessary for the application of the above spectral analysis is violated, and hence that these methods cannot directly be applied.

4. Turning now to field measurements, then what is measured is the power output due to unsteady wind.
Actually time series are recorded of simultaneous measured shaft torque, r.p.m. (often constant), electrical power and wind speed at some point in the vicinity of the wind turbine, usually at hub height.

Leaving aside the details of the recording technique, one experiences of course that instantaneous, simultaneous measurements of wind speed and either torque or electrical power, when plotted exhibit a considerable scatter.
This is due to the fact that one normally makes a point measurement of wind speed, whereas the power is an integrated

effect over the rotor disc, and to the fact that the distance between the wind turbine and the measuring tower makes the correlation (or coherence) between the instantaneous turbulent velocity field at the two places small.
Different methods have been proposed to reduce this scatter. One is conditional sampling and averaging over the sampled region (method of bins) [7]. Another is to make ensemble averages over times long enough to cover the region in the wind spectrum above the mesoscale gap. Averaging times of 10 minutes are usually considered to fullfill this requirement.
It has been indicated, [8], that application of the "methods of bins" gives rise to erroneous results when poor coherence exists between wind velocity measured at the met. tower and the wind at the turbine, i.e. for large distances between the two. Also, no theoretical arguments have been raised, justifying the application of this method.

Ensemble averages on the other hand seems to yield correct results as far as it gives the power due to the actual unsteady wind. In other words it gives the average value of power versus averagewind speed in a wind with the turbulent characteristics present on the day of measurement.
If now these turbulent characteristics do not change significantly from one day to another (due to different stability of the atmosphere f.i.) and the terrain in the vicinity of the wind turbine is homogeneous, then the power curve obtained in this manner should be the one necessary for calculation of the energy production from the wind turbine. In fact, the annual production of energy and the probability density for wind speed would be obtained from the very same kind of measurements.
At another site with different roughness lengths for the surrounding terrain, the result would be different, but it is felt that it is possible to establish a fairly accurate extrapolation to other surroundings.

5. This measured curve however is not the one which would be measured in a steady wind, and accordingly it is not to be compared directly with the curve calculated from aerodynamic theory. The reason for this being (a.o.) the abovementioned non-linear character of the stationary power curve.
A first approximation in correcting the calculated curve to the measured one could be made by simply approximating the calculated relation by a suitable analytic function and to calculate the average value of power under the assumption the frequency response of the wind turbine is unity for all frequencies below a suitable cut-off frequency of the order of say $\frac{\bar{u}}{R}$, where R is wind turbine radius.
In this way a correction will be determined which depends on the actual measured variance in wind speed , and if necessary also on higher order moments of the wind speed fluctuations.
In fig. 1 is shown the calculated power curve for the "Nibe A" wind turbine. A fourth degree polynomial can be made to approximate the calculated curve as shown.

If

$$P = A + Bu + Cu^2 + Du^3 + Eu^4$$

and

$u = U + u'$, with U as the mean and u' the fluctuating part of the wind velocity, then

$$\bar{P} = P(U) + \overline{u'^2}(C+U(3D+6EU)) + \overline{u'^3}(D+4EU) + \overline{u'^4}\ E \quad ;$$

In the case of a Gaussian probability density distribution for u' , then

$$\overline{u'^3} = 0 \qquad \text{and} \qquad \overline{u'^4} = 3(\overline{u'^2})^2$$

$\bar{P}$ is then the quantity to be compared with the measured mechanical power output.
For the power curve shown on fig. 1, with $\sqrt{\frac{\overline{u'^2}}{U^2}} = 0.15$

$\frac{P(U)-\bar{P}}{P(U)}$ is about 8% for $U \simeq 14$ m/s, zero for $U \simeq 9$ m/s and about -14% for $U \simeq 7$ m/s .

"Nibe A" is stall regulated.

For a wind turbine with pitch regulation the control system dynamics must be taken into consideration.

6. Another aspect of power output which is of interest, is the fluctuations set up due to structural dynamic effects, triggered both by the gustiness of the wind and by wind shear and tower shadow effects. Also the system into which the power is fed, viz. generator and grid, does act as a dynamic system with an eventual feed-back on the power measured.
The frequency range of interest in this case is from 1 - p upwards.
It is however beyond the scope of the present note to discuss in what way an analysis should be carried out in order to obtain a proper comparison between measured and calculated data in this frequency range.

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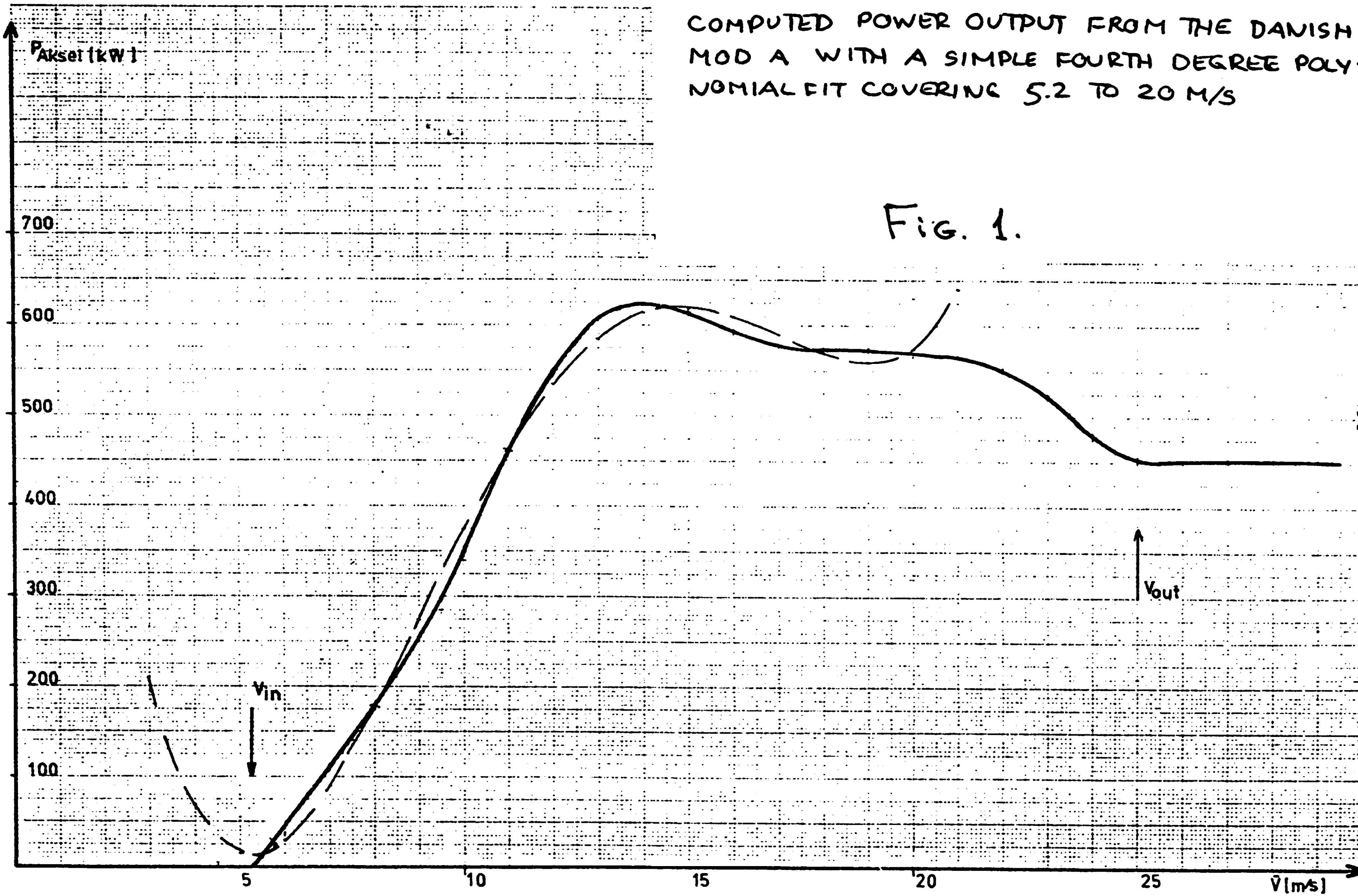


COMPUTED POWER OUTPUT FROM THE DANISH MOD A WITH A SIMPLE FOURTH DEGREE POLYNOMIAL FIT COVERING 5.2 TO 20 M/S

Fig. 1.

Testing And Evaluating Of LS/WECS - The Meteorological Approach.

by

Dr. Hans Schroers

University of Munich

Meteorological Institute

Introduction

Designing and putting up a windmill somewhere in order to gain energy by wind the following questions will arise:

1. Location
2. Wind profile
3. Extreme wind velocities
4. Gust factors and profiles
5. Power spectra of wind
6. Horizontal and vertical correlations

The first two items are very important to economic use. The next items are of considerable importance to savety against fracture.

The second part deals with instrumentation of wind measurements and presents a plant for determing gusts.

If nothing else is mentioned all graphs, slides and data refer to strong winds and storms in flat and open area. Strong winds and storms are defined as wind velocities of 10 m/s and greater in a height of 10 m.

Location

Location is not dealt with in this paper because it is a result of climate, especially of wind climate and that is a matter of the national meteorological offices.

Wind profile

In meteorology a logarithmic law is applied to increasing wind speed with increasing height.

$$v_z = \frac{v^*}{k} \ln \frac{z}{z_o}$$

A widely used alternative to the logarithmic law is the power law. This law is entirely empirical.

$$v_{z_1} = v_{z_2} \left(\frac{z_1}{z_2}\right)^{\alpha}$$

The difference is of no importance. But it is not possible to determine a fixed value for wind profiles in all atmospheric conditions. These simple laws are only valid for adiabatic atmosphere. The atmosphere is essentially adiabatic a short time after sunrise and a short time before sunset and in the case of high wind velocities (strong winds and storms). In all other cases the natural convection effects a considerable deviation from the logarithmic or power law. The value of this deviation can only be determined if the temperature gradient of atmosphere is known.

Another parameter affecting the wind profile is the roughness of ground. In logarithmic law this parameter is considered as z_o, the socalled roughness length, while in power law it is taken into account by the value of power itself. In fig. 1 a comparison between α and z_o is shown.

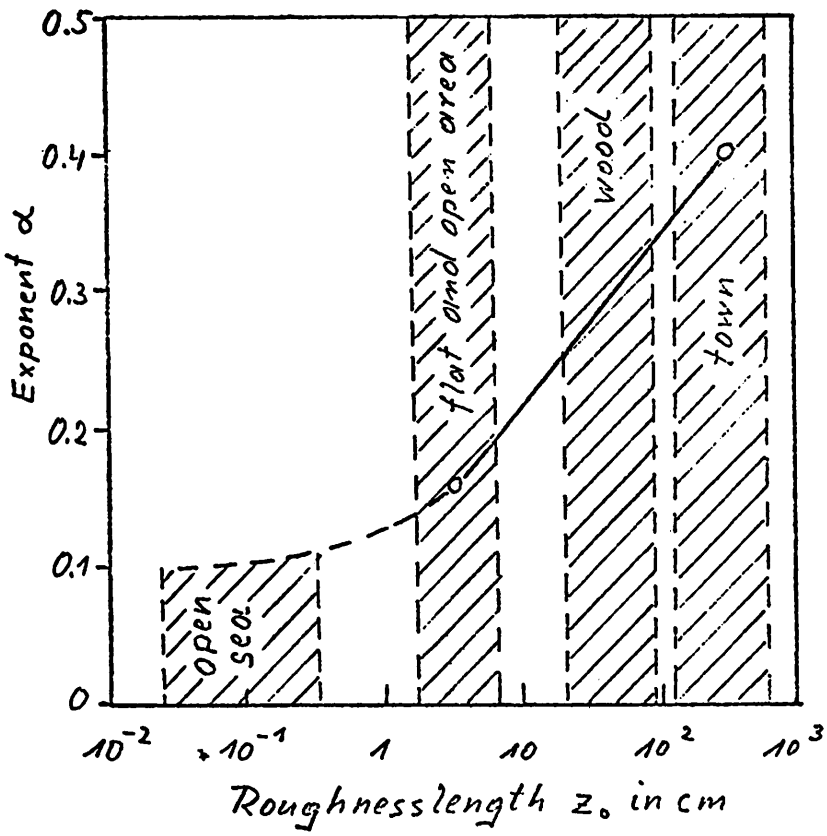


Fig. 1: Comparison between z_o of log-law and α of power-law (Davenport).

In the following tables some measured data of power profile are given. They are valid for 10 min. means of wind speed.

Strong winds and storms: $\alpha = 0.16$ $\sigma = 0.03$

Tab.1 shows some α and σ in relation to diffusion categories. The diffusion categories are mainly determined by means of temperature gradient, but also by some other parameters such as clouds, wind etc.

The variations of α and σ with low winds are shown in tab.2.

class	frequency in %	α	σ
I	8.4	0.39	0.12
II	12.9	0.37	0.13
III_1	57.9	0.36	0.15
III_2	13.9	0.18	0.07
IV	5.2	0.13	0.11
V	1.9	0.10	0.35

Tab.1: Variations of α and σ with diffusion categories (temperature gradient) valid for Hamburg (Manier a. Benesch).

wind categories in m/s	α	σ
< 1.5	0.51	0.14
1.6 - 2.5	0.38	0.11
2.6 - 3.5	0.30	0.16
3.6 - 4.5	0.25	0.13
> 4.5	0.19	0.11

Tab.2: Variations of α and σ with wind velocities (Manier a. Benesch).

Extreme wind velocities

In meteorology extreme wind speeds are always determined as probabilities once in 50 or once in 10 years reached and exceeded. For a special place, however, it is very difficult to define an exact value. Long-termed measurements are necessary, e.g. measurements have to be done for a period of 267 years in order to get these extreme wind velocities (once in 50 years) with a statistical assurance of 95% and an accuracy of ± 0.2 m/s. Such long-termed measurements do not exist. Only measurements for a period of 10 or 20 years are available at meteorological offices and it is their task to provide such probabilities for extreme wind speeds and for different regions, e.g. a lot of wind data measured on German coasts are avaluated in this month. The results will be published soon.

An example for getting these probabilities from relative short series is shown in fig.2.

The cumulative frequency distribution of all 10 min. means of wind velocities are printed in a Gaussian paper. The printed line shows the well-known skew distribution of wind speeds. In this paper the graph turns into a straight line at wind speeds > 8 m/s. That means high wind speeds are distributed normally. Extrapolating this line provides the probability of extreme wind velocities for a long time. But long series of observations of about 15 or 20 years necessary. Series of a period of 5 years are generally too short.

Gust factors and profiles

In meteorology it is usual to define a gust as a value of wind speed averaged over 5 seconds and the gust factor is defined by the quotient between maximum of gusts within 10 minutes and the averaged wind speed over these 10 minutes. Instead of one value in fig.3 a graph is shown which provides gust factors for any other times referring to the mean time of 10 minutes.

These gust factors resulting from a lot of measurements made by various authors are averaged values. The gust factors slightly decrease with increasing height up to 80 m. For greater heights detailed information is not

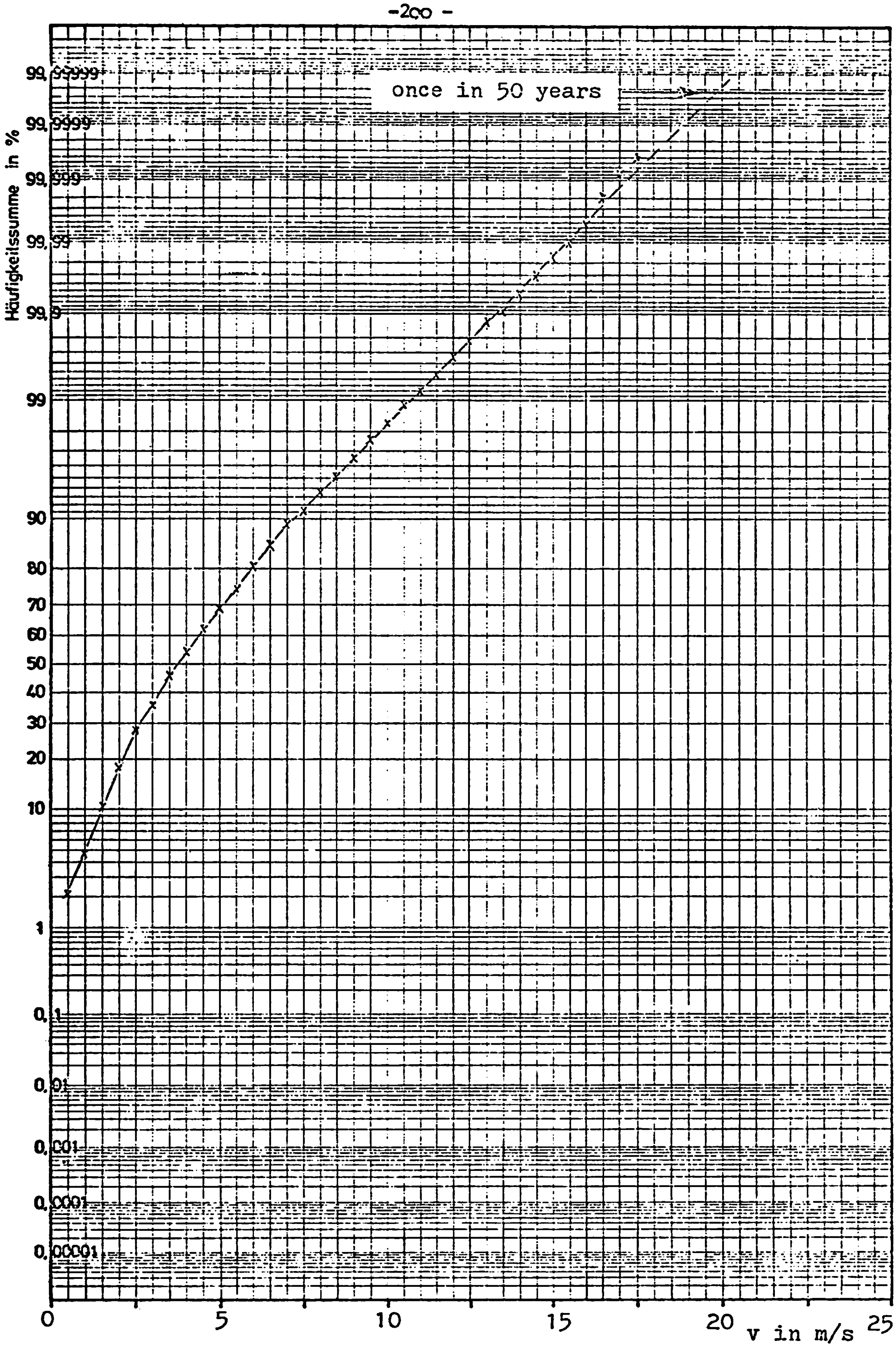


Abb.2: Summenhäufigkeit der Windgeschwindigkeit in 10 m Höhe.

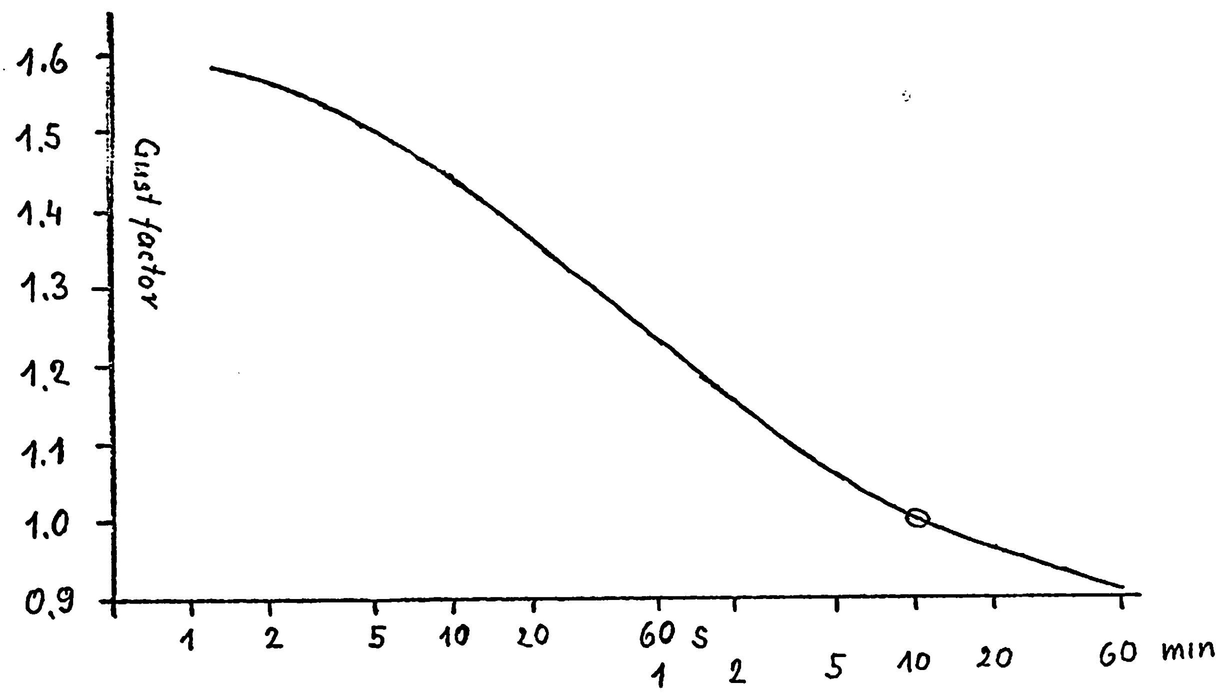


Fig.3: Gust factors dependant on mean times.

available. In the new DIN-Norm, "wind loads on structures" a gust profile is discussed. This gust profile is the same as the wind profile, fixed as power law, but another α is used. This α is 0.11, however it is only valid for gusts averaged for a period of 5 seconds. Based on mean wind velocities and gust factors in 10 m above ground mean gust velocities in other heights can be computed. Only statistics provide extreme values.

Power spectra of wind

Periods of about 20 seconds and below are in this case the interesting section of power spectrum. This is one part of dynamic turbulence which recently has been measured frequently. Especially the decrease with increasing frequency is well-known,so if the position and amplitude of power spectrum peak is known, you can extrapolate the decrease with the so-called -5/3 law, illustrated by fig.4.

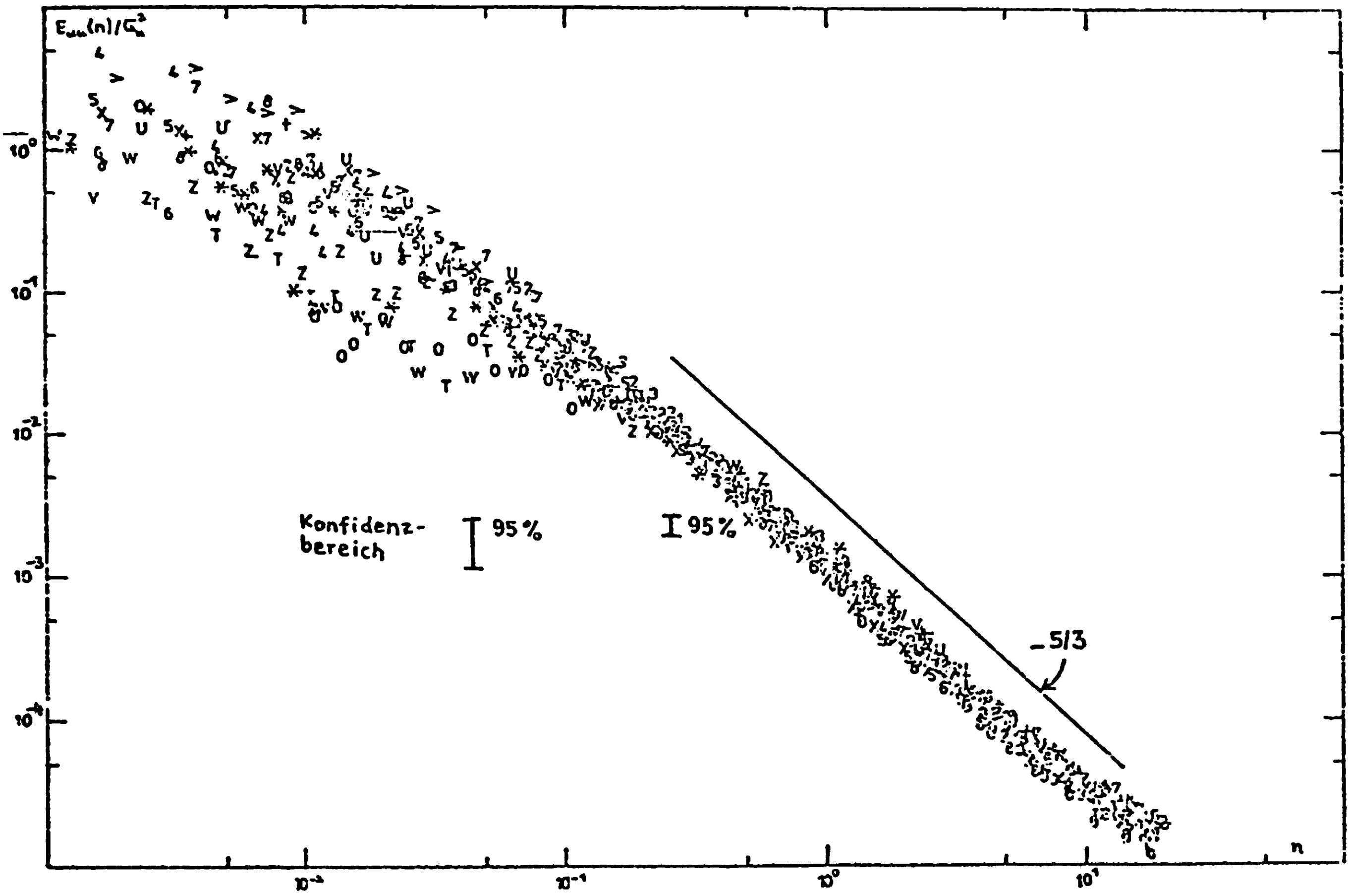
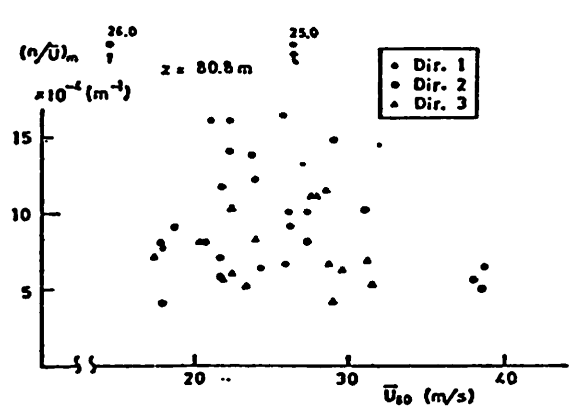


Fig.4: Observed wind spectra (Freytag 1973)

Position and amplitude of the spectrm peak, however differ very much from one run to the other. In fig.5 these great variations of position of spectrum peaks are shown. Therefore it is reasonable to draw the power spectrum as Shiotani has done it, shown in fig.6, and not as a line.

Fig.5: Variations of wave numbers of spectrum peaks with wind velocities.



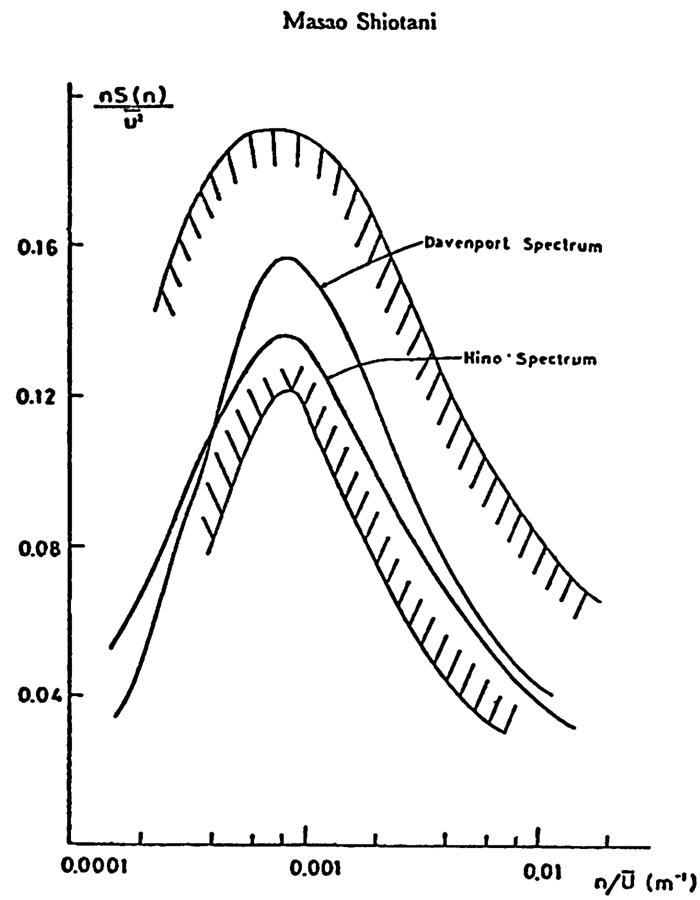


Fig.6: Observed power spectra at 80.8 m, and comparison with suggested power spectra.

Within this hatched section all his measurement points and some of other authors are located. At present statistics of power spectra do not exist, because it is obvious that only few runs have been made at one place. In future the task will be to realize long-termed measurements of power spectra.

Horizontal and vertical correlations

At present no results about horizontal and vertical correlations are available, because no data of horizontal correlation tests exist.

In order to gain these correlations a measurement program is just initiated in the northern part of Germany. These tests are made on three towers situated in a distance of 60 and 100 m from one to the other. These three towers are located at the edges of a triangle and are of a height of 40 respectively 80 m. The data are recorded since summer 1979. The results of the tests of vertical correlations up to 80 m and of horizontal correlations at least in 40 m will be published in 1980. In order to get not only some single results but also complete statistical data, it is intended to do these tests for a period of 2 or 3 years. Due to these long-termed measurements of wind velocities and gusts we have to use anemometers which resist storms without damage and which also have to produce data during this time. The only instruments resisting these loads are the cup anemometers.

It is always assumed that cup anemometers are not qualified for gust measurements, because of its inertia. Fortunately inertia time of cup anemometers is proportional to the wind speed. The inertia time decreases with increasing wind velocity. Therefore it is reasonable to characterize the inertia of cup anemometers by the proportional factor K or 1/K, because K is constant. The characteristic value 1/K has the dimension of m and is called inertia length. This length is that wind way the air has to cover until the rotations of the cups have approached the new wind velocity up to 37%.

For the tests just mentioned a small cup anemometer, shown in fig.7, is used with an inertia length of 5 m. This length is so small that gust measurements are possible at wind velocities of 5 m/s and greater by sampling every second. It is not reasonable to record data at wind speeds below that limit. That is a method to reduce data.

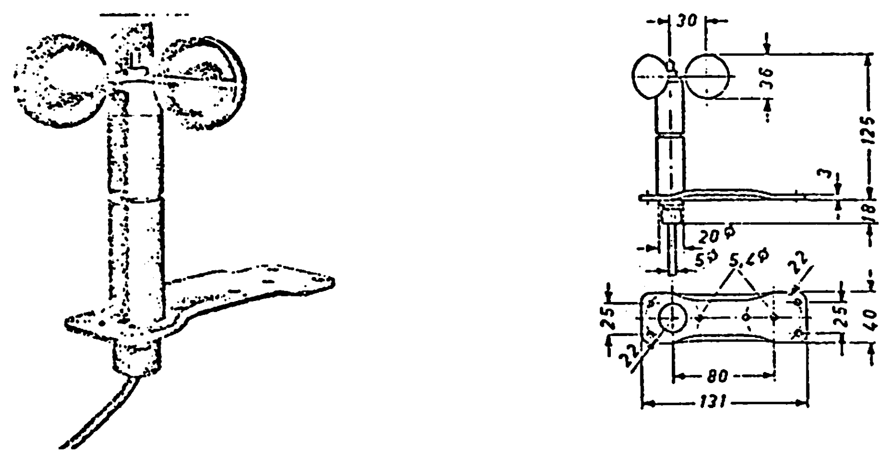


Fig.7: A small cup anemometer (1/K = 5 m)

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SITING TECHNOLOGIES FOR LARGE WIND TURBINE CLUSTERS[(a)]

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INTRODUCTION

The objective of the U.S. Federal Wind Energy Program is ". . .to accelerate the development, commercialization and utilization of reliable and economically viable wind energy systems" (ERDA 1977). To achieve this objective, the program is organized into several elements. The Wind Characteristics Program Element (WCPE), one of these elements, is managed for the U.S. Department of Energy (DOE) by Pacific Northwest Laboratory (PNL). PNL has the specific responsibility for providing the appropriate information on wind characteristics to those involved in:

- energy program planning and energy resource analysis
- selection of sites for wind energy conversion systems (WECS)
- design and performance evaluation of WECS
- day-to-day operations of WECS (Wendell et al. 1978).

Applied research and development within the WCPE currently focus on:

- developing effective siting technologies
- defining the wind energy resource
- providing information on wind structure and turbulence to designers
- investigating wind-forecasting techniques that would improve the integration of wind turbines with existing electrical networks.

This paper discusses the first of these activities as applied to large wind turbine clusters and describes a possible site-selection strategy for a large public utility that is considering the inclusion of WECS into its mix of generating equipment. The utility is assumed to be looking for areas where a

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(a) This paper was based on work performed under U.S. Department of Energy Contract No. EY-76-C-06-1830.

large number of megawatt-scale machines (say, 10 to 50 machines) can be placed in reasonable proximity. In this context, the term site refers to the location of a WECS cluster.

The site-selection strategy is conservative, partly because the large-scale generation of electricity by wind turbine generators is still a developing technology. Wind characteristics at a site will have to be thoroughly documented, because the nature of the wind at the site not only governs the energy output of the cluster, it also affects the service life of the wind equipment and both scheduled and unscheduled maintenance costs. Perhaps with experience, the site-selection process can be simplified. Certain steps may be found unnecessary, or requirements on the quantity and quality of wind data collected at each step may decrease. However, at this stage of wind energy development, a conservative approach seems prudent, even though such an approach is not cheap. Extensive measurements cost a great deal to make and to interpret, but a simple analysis shows that reasonable meteorological siting costs should be paid back very quickly through improved machine performance.

There are basically two ways to approach WECS siting: by "wind prospecting" and by wind-potential evaluation at a predetermined site. In wind prospecting, an area must be screened for high-wind potential before we can proceed with the siting steps that the two ways share: evaluating the site and developing the site. In the second way, a site has already been determined to be a high-wind area, and wind-related information has been gathered on the site, so the second way is simply an abridgement of the first. In this paper, we describe wind prospecting and discuss site-selection techniques and how they apply to the steps in wind prospecting.

SITE-SELECTION TECHNIQUES

Numerous techniques can be used to identify WECS sites. The following techniques have been examined in the Federal Wind Energy Program. Their applicability to the siting steps of wind prospecting is shown in Figure 1.

	LARGE-AREA ANALYSIS	MESOSCALE EVALUATION	CANDIDATE SITE SCREENING	CANDIDATE SITE EVALUATION	SITE DEVELOPMENT
NUMERICAL MODELING		X			X
PHYSICAL MODELING					X
BIOLOGICAL INDICATORS	?	X	X		X
GEOLOGICAL INDICATORS	X	X	?		
TOPOGRAPHICAL INDICATORS	X	X	X		X
SOCIAL & CULTURAL INDICATORS	X	X	X		

FIGURE 1. Applicability of Siting Techniques to the Various Steps in Wind Prospecting

NUMERICAL MODELING

Numerical models provide an objective method for estimating the effects of terrain on airflow and for interpolating wind data from locations for which wind observations are available to locations for which none are available. The accuracy of these simulations depends on the accuracy and density of the input data and the amount of realism inherent in the mathematical relationships that make up the model.

PHYSICAL MODELING

Flow over terrain may also be modeled by placing a scaled representation of the terrain in a suitably designed wind tunnel. This approach can yield useful information as long as the horizontal length scale of the modeled region measures no more than a few tens of kilometers and the portion of the atmosphere to be studied is the lowest few hundred meters. Wind tunnels are limited in their ability to simulate all aspects of flow over terrain; however, they simulate the effects of small-scale terrain features on nearly neutral flow better than currently available numerical models.

BIOLOGICAL INDICATORS

The shapes of certain species of trees are good indicators of high winds. Trees are particularly useful in regions where large, local variations in wind speed can be expected or in regions where wind data are sparse (Hewson and Wade 1977; Putnam 1948).

GEOLOGICAL INDICATORS

The wind produces certain features of the land surface, such as sand dunes. These eolian features are easily detected from satellite or aircraft photographs. The existence of eolian features, however, is not a guarantee of persistently strong winds. Eolian landforms can be caused over a period of years by occasional strong winds (Marrs and Koprina 1978).

TOPOGRAPHICAL INDICATORS

Empirical guidelines describing the general effects of terrain or surface obstacles on the wind are invaluable in interpreting the results of numerical and physical modeling studies and measurements. Topographical guidelines are either based on a physical understanding of how such features affect flow or on experience gained through observation. Historically, these guidelines have been applied to the siting of wind machines without supporting measurements (Golding 1955; AWEA 1977).

SOCIAL AND CULTURAL INDICATORS

A valuable source of indirect wind information can be found by examining land-use patterns and by questioning people who live or work in areas that are expected to be windy. Population centers are good indicators of wind: We do not expect large population centers to be in areas with high wind-energy potential. Agricultural uses of the land are also indicators: windy areas are more likely to be used for grazing than for row crops. Other indicators could be the locations of snow fences along the highways or the locations of frequent wind damage to power lines.

WIND-PROSPECTING STRATEGY

The goal of the wind-prospecting strategy outlined here is to identify several WECS clusters that could be developed sequentially. In choosing these sites, the issues of land use, accessibility, public acceptance, and proximity to existing transmission lines must be considered in addition to wind power potential. A proper combination of sites would be one in which the net power output best matches the load and generating characteristics of the utility. The seasonal and diurnal characteristics of the wind are therefore important, since these characteristics determine the seasonal and diurnal characteristics of wind-generated power.

Terrain should be of particular concern in making siting decisions. Locating WECS clusters in flat areas could result in lower costs for siting evaluations and operation, since wind characteristics tend to be more benign over gentle terrain. On the other hand, the more rugged the terrain in and around the site, the greater the horizontal variability in the wind resource and the greater the likelihood of large wind shear and turbulence, which could result in higher costs for site evaluation and for machine operation.

Figure 2 is a flow chart outlining the wind-prospecting strategy that leads to the development or rejection of sites. The major steps in this strategy are best described by considering each one in sequence.

LARGE-AREA ANALYSIS

The first step in a large-area analysis is to examine pertinent wind resource assessments for the utility's service area and any additional wind-related information the utility might have. When land use, power transmission corridors and accessibility issues are considered along with the wind resource assessments, smaller areas are identified for more detailed study (see Figure 3).

Resource assessment, as addressed in the WCPE, refers to the large-scale analysis (i.e., the United States or a collection of several states) of the wind energy resource by estimating the wind power potential of a given area and the distribution of the wind energy within that area. If a regional assessment is available, the large-scale analysis takes little time (more

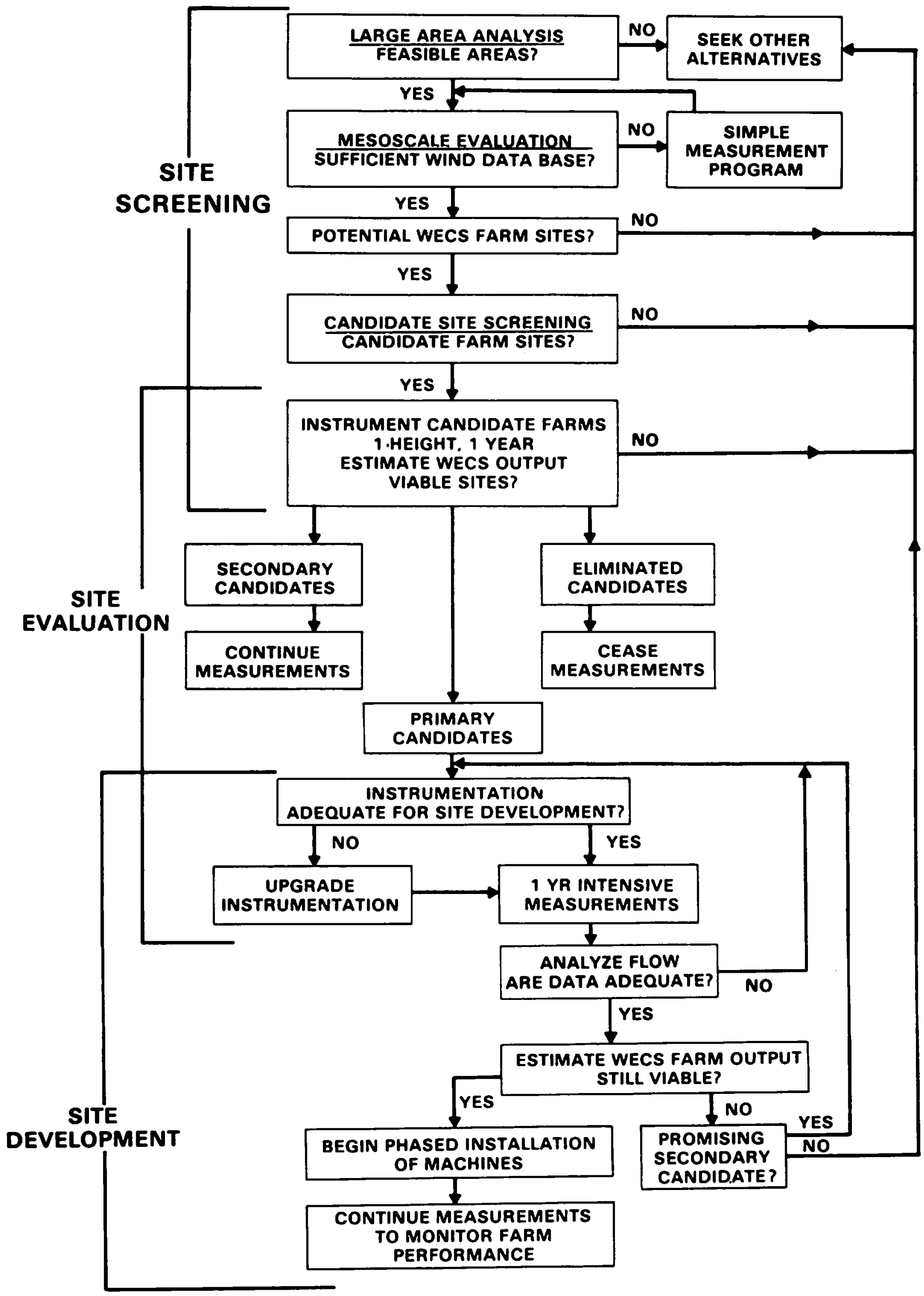

FIGURE 2. A Strategy for Wind Prospecting

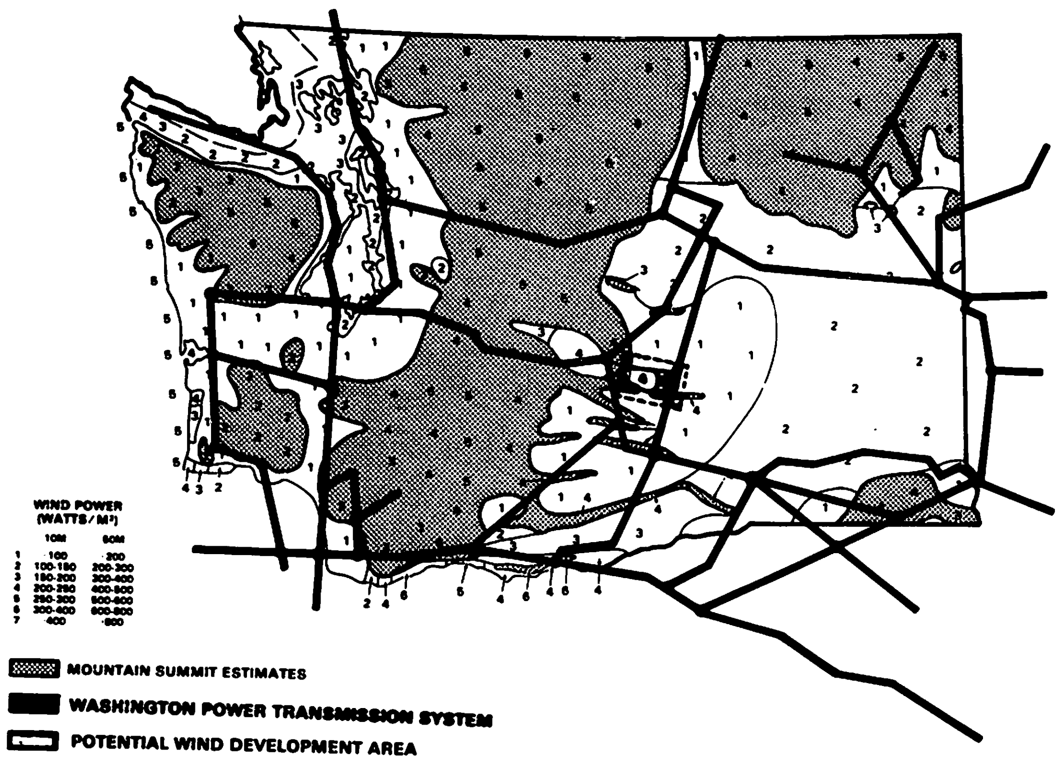

FIGURE 3. Large-Area Analysis Showing Major Power Transmission Lines Overlaid on the Annual-Average Wind Power Map.

FIGURE 4. An Example from the Northwest Regional Assessment Showing the Average Winter Wind Power Flux (w/m^2) for the State of Washington. Shaded areas indicate mountainous terrain.

time is spent finding high-wind areas that satisfy the nonmeteorological site criteria).

A regional wind-power resource assessment for the Northwest (Renné and Elliott 1978) has shown that significantly higher resolution can be obtained from existing meteorological data that were not used in earlier assessments and from responsible use of extrapolation techniques that can be used to make estimates of the resource in areas where data have not been collected. Figure 4 is an example from the Northwest Regional Wind Energy Atlas that shows an estimate of wind power density over the state of Washington in winter. The wind resource in eleven other regions spanning the United States will be analyzed according to the Northwest assessment prototype.

MESOSCALE EVALUATION

If wind power is feasible, the large-area analysis will have identified several attractive areas with dimensions on the order of 100 km by 100 km. The wind energy potential within one of these areas varies considerably, and a single area could contain several potential wind clusters. The next step is screening these areas to identify potential wind clusters (see Figure 5). (Figure 1 shows the techniques that could be used.) For areas without data, a supplemental wind measurement program may be required.

The amount of wind data required depends upon the terrain and meteorological complexity of the area. If the topographical forcing of the flow is strong and the seasonal and diurnal variations in forcing are large, data spanning at least one year are required for an analysis of the flow characteristics of the region.[a] The surface data should come from those key locations that provide the most information on the mass flow through the area: major valleys parallel to prevailing flow, major passes, and major ridges perpendicular to the prevailing flow. Numerical models may be used to assist in this analysis. Models require input data that are representative of a time that is short compared to the time scale of the changing forces, yet long compared to the turbulent motions that are insignificant to the total mass flow. Typical

(a) Here an analysis is an estimate of the flow at all points in a given region subject to the constraints of the physical laws governing the atmosphere.

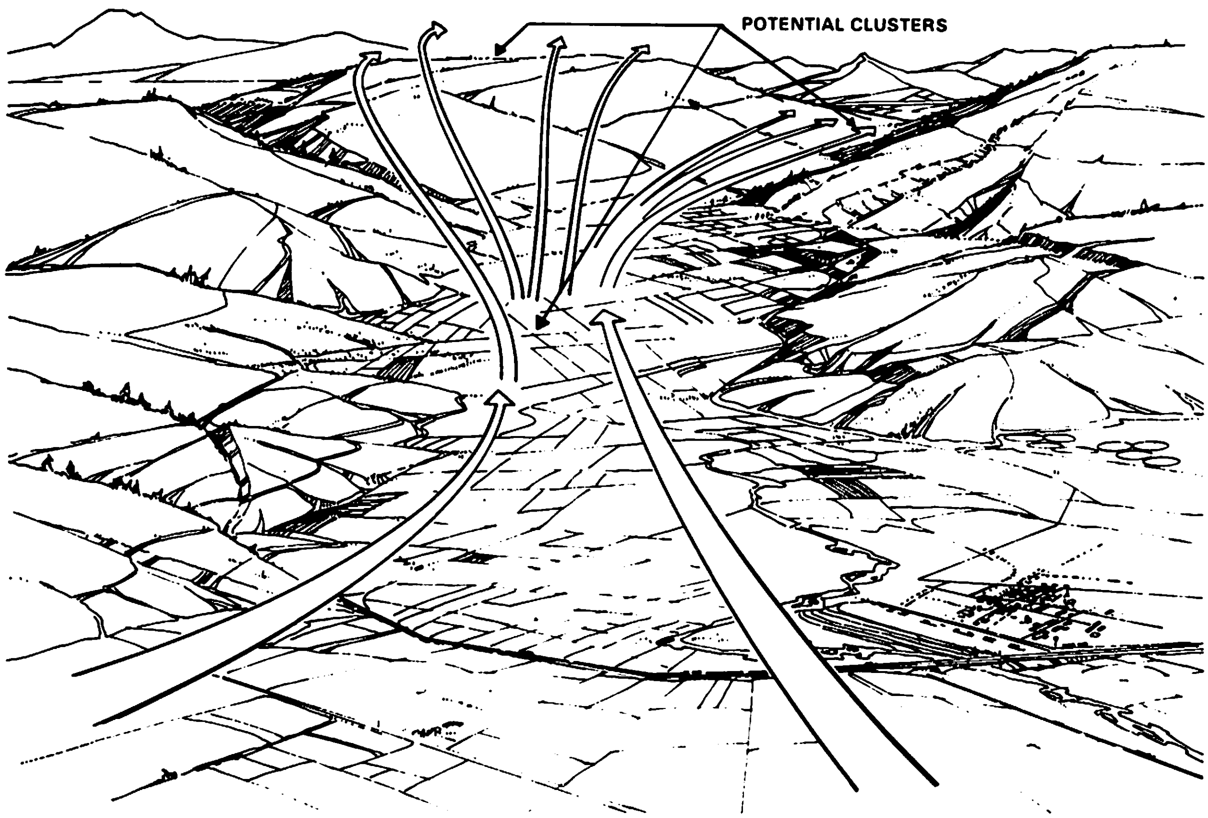

FIGURE 5. Mesoscale Evaluation

data requirements of a fairly simple numerical model simulation would, therefore, be:

- synchronous measurements of one-hour averages of surface wind speed and direction at key locations
- vertical profiles of wind speed and direction.

Numerical models assist in mesoscale wind energy analysis by simulating a representative cross section of the climatology. We cannot, of course, know *a priori* that a given day is representative; therefore, selection of the cases for simulation can only be done once the season or year of data has been collected and analyzed.

A rigorous mesoscale analysis that uses the supplemental wind data described above can provide a great deal of information about the entire regional flow, whether or not anemometers were located in what the analysis showed to be high-wind areas. A less rigorous more risky approach may be taken, described more appropriately as mesoscale wind documentation rather than mesoscale wind analysis. Here, supplemental data are collected at what are presumed to be the windiest locations. The techniques listed in Figure 1 are used to estimate these locations. Numerical models may be used as a guideline here, too, but one must assume the input climatology. If the model's indications of high wind areas are very sensitive to the input, an analysis probably needs to be performed.

Mesoscale wind documentation can be obtained with equipment as crude as wind-run anemometers. However, information on hourly wind speed and direction as a function of time-of-day is better, because the information can be used to compute WECS power output more accurately. This type of data can be obtained from simple systems such as mechanical weather stations or from "smart" data loggers employing microprocessors to sample and bin the data.

CANDIDATE SITE SCREENING

After a number of potential sites for multiple WECS installations have been identified through large-area analysis and mesoscale evaluation, the sites need to be further screened. This screening is accomplished by site visits (see Figure 6). During these visits, the surrounding terrain is examined, and any small-scale terrain features or obstacles that could affect wind characteristics at the site are noted. Soil conditions are also examined. Site screening is not a time-consuming process and, depending on the number of sites, can be completed in a few weeks to months.

Valuable information on wind characteristics at the site can be obtained by measuring the wind profile, using wind-sensing kites or instrumented tethered balloons, and by examining the vegetation. Profile measurements made during site visits would primarily be used to identify obvious potential hazards, such as flow separation zones and the turbulence and high wind shear that accompany them. The measurements cannot provide a meaningful profile climatology because they are such a small set of observations.

FIGURE 6. Candidate Site Screening

CANDIDATE SITE EVALUATION

Candidate site evaluations determine more accurately how wind machines would perform at each of the sites and ascertain the combination of sites that would result in power output characteristics best matching the needs of the utility (see Figure 7).

At this stage of the site-selection process, wind data are needed at only one level -- as near hub height as possible. In flat terrain, a single measurement location will be sufficient; in more complex terrain, measurements at several places may be required.

Although the length of time data must be collected is uncertain at present, at minimum two years of data are needed to establish the optimum mix of WECS clusters from a set of candidate sites. However, one year of data should be enough for identifying the leading sites in terms of total annual

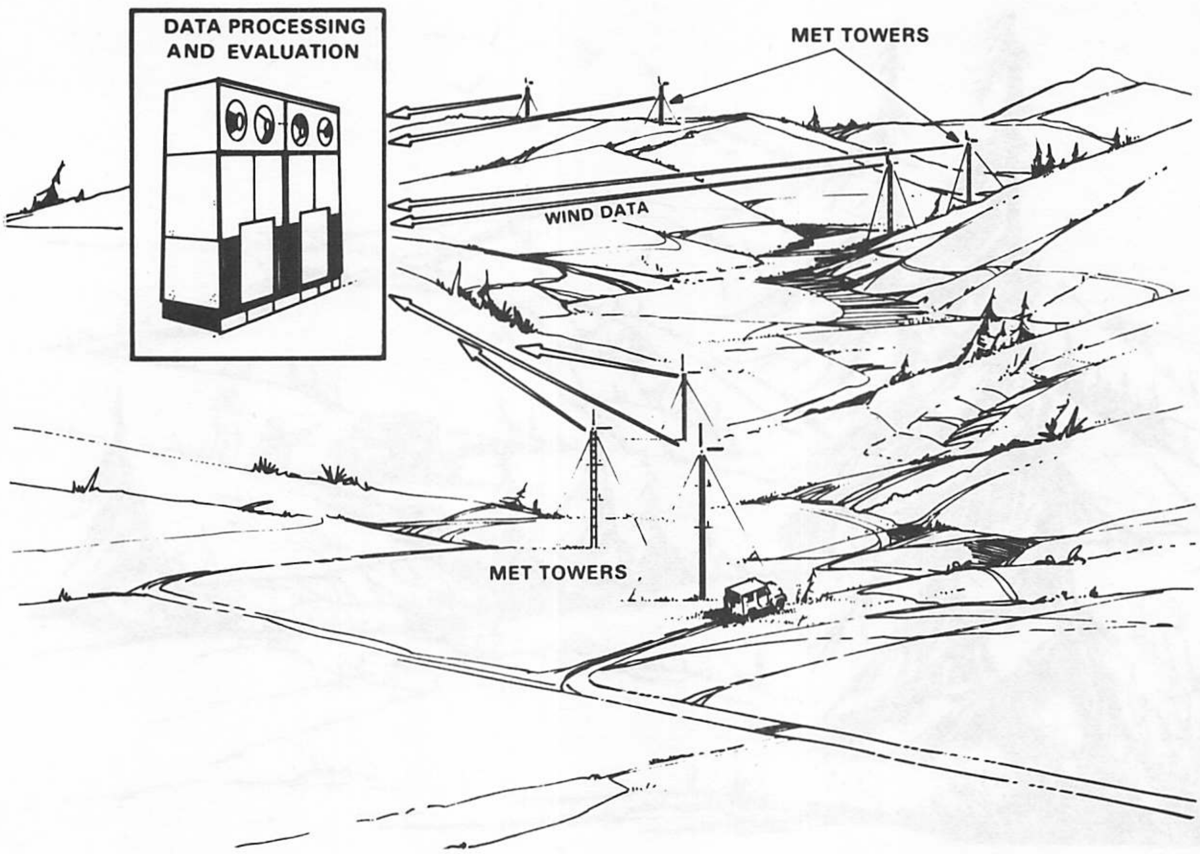

FIGURE 7. Candidate Site Evaluation

energy production, unless the year was climatologically abnormal. Experience with the 17 candidate sites in DOE's MOD-OA demonstration program showed no significant changes in site ranking by annual energy production when a two-year record was used instead of a one-year record.

The data required during site evaluations are wind speed and direction. Hourly averaged wind speeds have been assumed to be adequate to estimate the power output of WECS, since a utility's estimates of hourly loads may not be particularly accurate.[a] Wind direction measurements are needed to determine the principal wind power directions and to gauge wind direction variability. The variability in wind direction could be an important factor affecting WECS

(a) More analysis of machine performance of large turbines is required before we can say how accurately machine performance may be modeled by hourly data.

operations, since most machines are designed to track changes in wind direction to minimize the degree of off-axis operation. Utility-scale machines require large motor-driven yawing mechanisms; therefore, a site where the wind is fairly steady is clearly preferable to one with large, capricious changes in direction.

One way of logging wind information is to record time series of hourly averaged wind speed and direction. Standard deviations of wind speed and direction defined with respect to the hourly averages should be recorded to provide information on turbulence levels and wind direction variability. Data could either be recorded at the location of each instrument or transmitted to a central recording station. Recording the data at a central location provides obvious advantages in managing the data and in maintaining system reliability; however, it requires large initial expenses. Recording data in a time-series format provides the greatest flexibility for future use of the information. The data can be used either to produce statistical summaries of wind characteristics, such as wind speed probability functions, or to model the dynamic characteristics of a network of wind generators. The disadvantages of a time-series format lie in the volume of data produced.

Information on wind characteristics at candidate sites can also be logged by a smart data logger. Such a device accumulates hourly averages of wind speed and direction in bins corresponding to the time of day and intervals of speed and direction. Data are recorded in a solid state memory; thus, data can be retrieved more reliably than when it is recorded on mechanically driven tape or strip chart recorders. The smart data logger can produce histograms of speed, direction and their variances as a function of time of day. The principal advantage of the smart data logger is that it reduces the amount of subsequent data processing, although flexibility is decreased (e.g., the ability to model dynamic characteristics of a WECS network is lost).

The smart data logger also shares several disadvantages with other on-site data-logging options. An on-site logger must be serviced on a rigid schedule to prevent loss of data either through saturation of memory or by running out of tape. Large blocks of data can also be lost if the instrument malfunctions. The only checks on system operation are during the scheduled maintenance visits.

SITE DEVELOPMENT

After data are collected at the candidate sites for one year, the basic characteristics of the wind resource at each site will have been established. An evaluation of the resource magnitude and its seasonal or diurnal behavior at each site may lead to the selection of a given site as the primary candidate that best matches the needs of the utility. A few sites may be eliminated and some sites may become secondary candidates where candidate site evaluation should continue (see Figure 2).

At the primary candidate site, the WECS cluster development stage begins (see Figure 8). The three main objectives are:

1. to determine the location for each machine to be placed in the cluster,
2. to estimate the power output characteristics of the cluster,
3. to document those wind characteristics that affect WECS operation and service life.

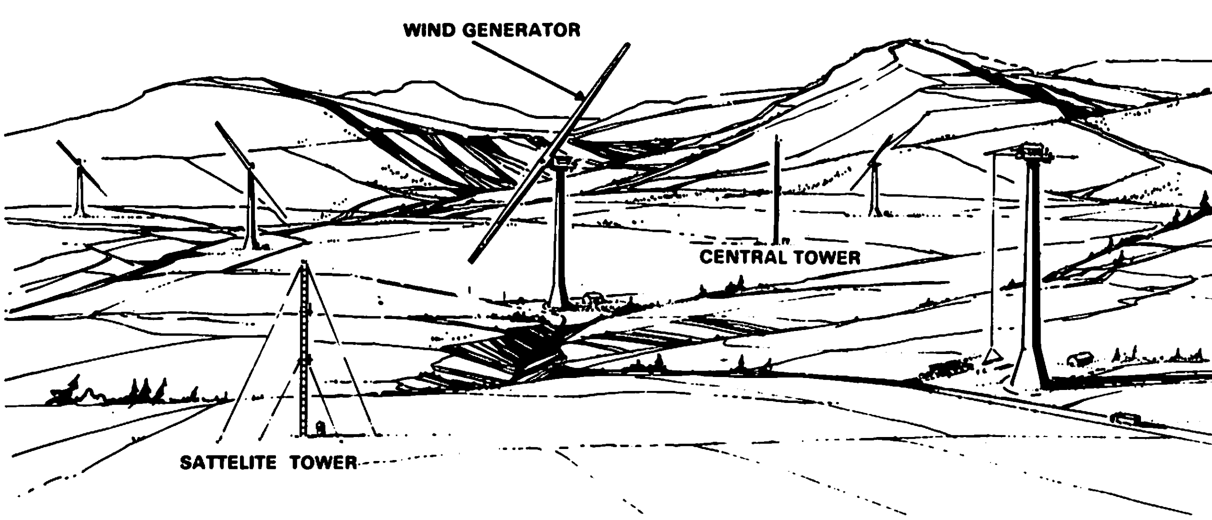

FIGURE 8. Cluster Development

Determination of machine locations requires detailed measurements, followed by an analysis of the flow through a section of the atmosphere 100-m deep and spanning the horizontal extent of the proposed WECS cluster. The analysis techniques would include subjective analysis, and numerical and physical modeling. It is possible, though not probable, that the analysis may indicate the need for a longer period of data collection, an even more extensive data collection network, or both. If so, the site development cycle would be repeated (see Figure 2).

The second major objective of the WECS site development stage is to estimate the power output characteristics of the proposed WECS cluster. Currently, insufficient experience with utility-scale wind machines exists for a definitive statement to be made on what data are needed to make this estimate. This is particularly true for very large systems in the megawatt range with rotor diameters up to 100 m. However, in a conservative approach, wind data collected should be sufficient:

- to model time variations in power output, both for individual machines and for the entire cluster;
- to tune control systems governing machine start-up and shutdown, since behavior in the neighborhood of these wind speeds affects both net power output and service life;
- to evaluate the effects of wind direction changes on the operation of yawing mechanisms.

In addition, frequency of icing conditions information is desirable since even under light icing conditions, the personnel hazard (due to ice throwing by the rotor) may require periods of shutdown.

The third major objective of this stage is to document those wind characteristics that affect WECS operations and service life, i.e., extreme wind events and turbulence. Techniques that predict the frequency of occurrence of extreme wind events with high precision and confidence have not been developed. It is expected that if and when they are developed, the input data needed by these techniques will not require any measurements beyond those made to satisfy the other two objectives discussed above. Documenting the turbulence characteristics, however, requires a more specialized measurement system.

Measurement Systems - Flat Terrain

The layout of a wind measuring network for site development will depend on whether the goal is merely to map the mean flow field and locate individual machines at the locations with highest mean wind speed or whether the goal is to model and to evaluate the performance of each machine in an array. For clusters of large machines, we assume that the latter goal would be the case.

The layout of a wind measurement network also depends on terrain complexity. Flat terrain is obviously the simplest. Choosing the sites for individual machines in an array will depend very little on the terrain, since the most significant differences in average wind characteristics will be due to surface roughness changes or to the wake effects of the machines themselves.

Installation of a central tall tower at the site, as shown in Figure 8, is strongly recommended. Significant low-level wind shears, for instance, can be experienced, even over flat terrain. It is important to document whether these shears exceed the design limits of the machines under consideration. Considering the capital investment a WECS cluster represents, knowledge of wind characteristics across the rotor disk would seem essential.

The tall tower should be located at the center of the planned WECS array. This will enable an assessment to be made of the effects upstream machines may have on site wind characteristics as installation of the array proceeds.

Even over flat terrain, satellite towers would be required to supplement the data from the tall towers. Satellite towers would serve:

- to monitor the flow approaching the WECS array,
- to fine-tune the array layout,
- to model the short time-scale performance characteristics of machines within the array.

The satellite towers would have to be instrumented at only one level - as close to hub height as possible.

The number and the placement of satellite towers for monitoring approach flow conditions is very straightforward. They are set by the prevailing wind directions and the placement of the array.

Unless machines are spaced more than ten rotor diameters apart, wind characteristics within an array will be dominated by wake effects from upstream units. Eventually, the arrangement of machines within arrays on flat land will be set by empirical guidelines. Experience should also indicate how machines within the array will perform. Until such experience makes it unnecessary, a satellite system within the array is recommended. The satellite system will document the horizontal variability of wind characteristics within the array more thoroughly than a single tower. Information from the satellite towers would be used to document how the installation of machines in the array is affecting wind characteristics. These data could be used to model how new machines would behave and would be used to fine-tune the array design.

The arrangement of towers within the array would be set by the array design. Over flat land, WECS arrays will be in some sort of geometrical pattern, probably a diamond lattice as viewed from the prevailing wind direction. One or two satellite towers are recommended per row of machines, where a row is defined perpendicular to the prevailing wind direction. Staggering the towers will result in the best coverage.

Measurement Systems - Hilly Terrain

For hilly areas (i.e., local relief is greater than 50 to 100 m), the placement of machines within a WECS array will be dominated by the morphology of the terrain and the orientation of the principal terrain features to the prevailing wind directions. Again, information will be needed on the vertical structure and horizontal variability of the wind over the site. In contrast to siting in flat terrain, wind measurements will play a more important role in documenting the characteristics of the flow over the site and in locating individual machines in the WECS array.

Physical modeling can play a very important role in planning the layout of a WECS array in hilly terrain. Placing a detailed scale model in a suitably designed wind tunnel and examining the flow over the model for the predominant wind directions provides guidance on the locations for individual WECS in an array and on the locations for the wind measuring systems needed to document the flow.

As in the flat terrain case, a centrally located tall tower will be the heart of the measurement system. Satellite systems consisting of wind speed and direction sensors at a single height would be placed according to the guidance of physical modeling and experience. The satellite systems would probably be more numerous than for a flat site.

If the terrain within the site is particularly complex, a single tall tower may not be adequate for accurately characterizing the vertical structure of the wind for the entire array. Again, physical modeling would be helpful in determining if this were the case. However, it is doubtful that large machines would be placed in a site so complex that significant differences in the vertical structure of the wind would be experienced over a distance equal to the size of a WECS array.

As data are collected from the site measurement system, they should be analyzed. Simple numerical models can be used to create an objectively analyzed field from a set of distributed point measurements. Analyzed wind fields corresponding to the important wind directions would be compared to the results of physical modeling. These comparisons would determine whether flow over the site was behaving as expected and whether the existing measurement system was adequate.

Data Requirements

At the tall towers, wind speed and direction measurements would be required at a minimum of three levels: hub height, near the bottom, and the top of the rotor disk. Data sampling rate for the tall tower systems would be four times the angular speed of the rotor of the machines under consideration. This rate will be adequate to resolve vertical wind gradients and to evaluate their effects.

Sampling rates for the satellite towers should be compatible with the response characteristics of the machines. The principal purposes for modeling the behavior of the individual units are to simulate machine start-up and shut-down operations and to model short-term fluctuations in power output from the array. In order to do the latter, only wind gust scales greater than the distance between machines in the cluster would need to be resolved. Power fluctations, due to smaller gusts, should show little coherence between machines and would have no effect on array output. Given a minimum spacing of five rotor diameters, a sampling rate of five per minute would be adequate for modeling power output (Pennell et al. 1980). This sampling rate would also be compatible with the rate required to simulate machine start-up and shut-down procedures.

The measurement system described above would produce a large amount of information, particularly if the data were continuously sampled at the maximum rates for both the tall and satellite towers. Data could be recorded on two time scales: the basic data set would be time series of hourly averages of wind speed, direction, and associated variances at each tower; the second would be recorded on a separate system at high sampling rates.

The basic data set would satisfy most of a utility's needs (assuming machine performance can be adequately predicted with hourly data), since this is the finest time scale in current utility planning models (Marsh 1979).

The second data set would not be needed all the time, since analysis of a small number of significant or representative events should provide the information needed. The recording of high sample-rate data could be keyed to wind speed ranges or wind directions of interest, or the data could be recorded on a continuous loop that would retain two or three days of information. Retention of the data for this period would allow sufficient time to retrieve information on significant events. These systems that sample or retain only a fraction of the data may prove to be unnecessarily complex, since the costs of archiving and processing all of the high sample-rate data are not large when compared with the costs of the data measurement system. Retaining all data reduces the possibility that crucial information could be lost.

After sufficient data have been collected and analyzed, individual machines can be located and the output of the entire cluster estimated. If the cluster meets the utility's needs, installation could begin, assuming a phased program. In a phased program, on-site experience could be obtained before a complete commitment is made to install all the machines, and modifications could be made to another cluster layout as additional data are gathered on machine operations and the wind resource.

A commitment to install machines at a site could be made after two years of collecting on-site data (one year in the site evaluation stage and one year in site development). However, a reasonable estimate of the interannual variability in power output could not be made with so little information. Some utilities may want to base a decision on a worst-wind-year-basis. Statistics representing a poor year might be determined by examining data from nearby locations with long-term wind records. However, such an analysis should be interpreted with caution. Little evidence exists that indicates that wind data can be reliably extrapolated from one location to another, especially in regions of complex terrain and with complicated meteorology. Moreover, very few locations have anemometers that have been fixed in position and altitude for long periods. Changes in wind characteristics, due to changes in anemometer location, are frequently greater than the interannual variability.

CONCLUSION

Site selection for large wind turbine clusters requires thorough documentation of the wind characteristics at the site, because of the influence these characteristics will have on the economics, operations, and service life of the wind turbines.

The wind prospecting strategy can be used by a utility to determine specific locations for each wind turbine in a cluster of 10 to 50 or more machines. This strategy consists of five main steps:

1. large-area analysis. The utility service area is screened for potential high-wind-power area with available land in reasonable proximity to transmission corridors.
2. mesoscale evaluation. Potential high-wind areas, identified by the large-area analysis, are screened and a number of potential candidate sites are identified.
3. candidate site screening. Visits are made to each potential candidate site. Some sites are eliminated during this step because of inaccessibility, soil or terrain conditions, or if site examination and measurements indicate excessive and frequent turbulence or wind shear.

4. candidate site evaluation. The candidate site screening steps are instrumented and sufficient measurements are made to make an economic assessment of the wind resource. If the site appears economically viable, the fifth step begins.

5. site development. Specific locations for each machine are determined, estimates of the cluster output characteristics are made, and installation of machines begins.

The key to site selection is knowing what and where to measure. Siting techniques to be used at the various stages of the wind-prospecting strategy were discussed. These techniques help determine where to measure. What to measure at a site is still a moot question. We have made suggestions on what data are needed at what sampling rates. These are based on the assumption that until further experience in siting large clusters of wind turbines is in hand, thorough documentation of wind characteristics affecting machine and cluster output characteristics, operation strategies, and service life are necessary.

Many of the recommendations presented here are based on theory, since no one has sufficient experience to speak with authority on this subject. Still, large utility-scale machines are being produced and will have to be sited. Experience with these initial installations will be critical in evaluating current siting approaches and in defining the crucial characteristics of a good wind turbine site.

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TWO METHODS FOR CORRELATING WIND MEASUREMENTS WITH THE POWER OUTPUT OF A 200 KW MOD-OA WIND TURBINE

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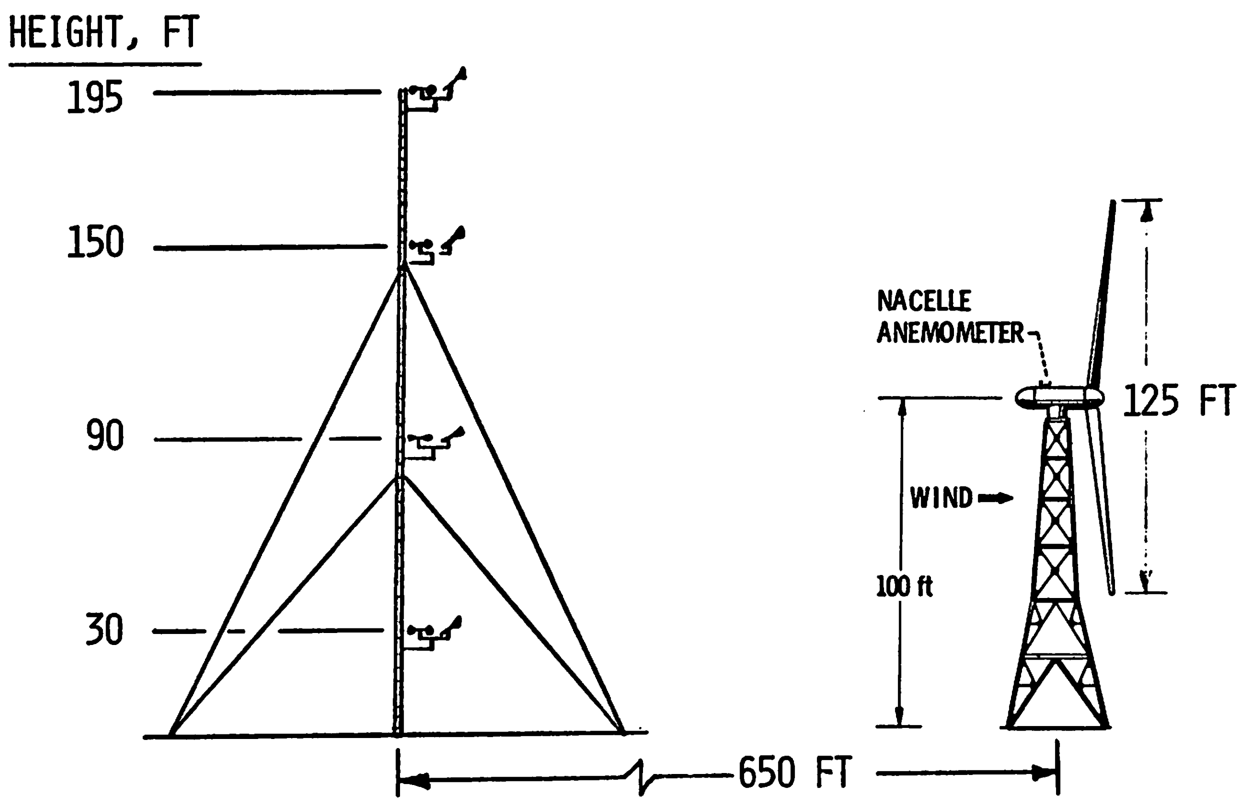
FOR PRESENTATION AT:
EXPERT MEETING ON DATA ACQUISITION AND ANALYSIS FOR LARGE-SCALE WIND ENERGY CONVERSION SYSTEMS, SEPT. 26-27, 1979, BOONE, NORTH CAROLINA

CONTENTS

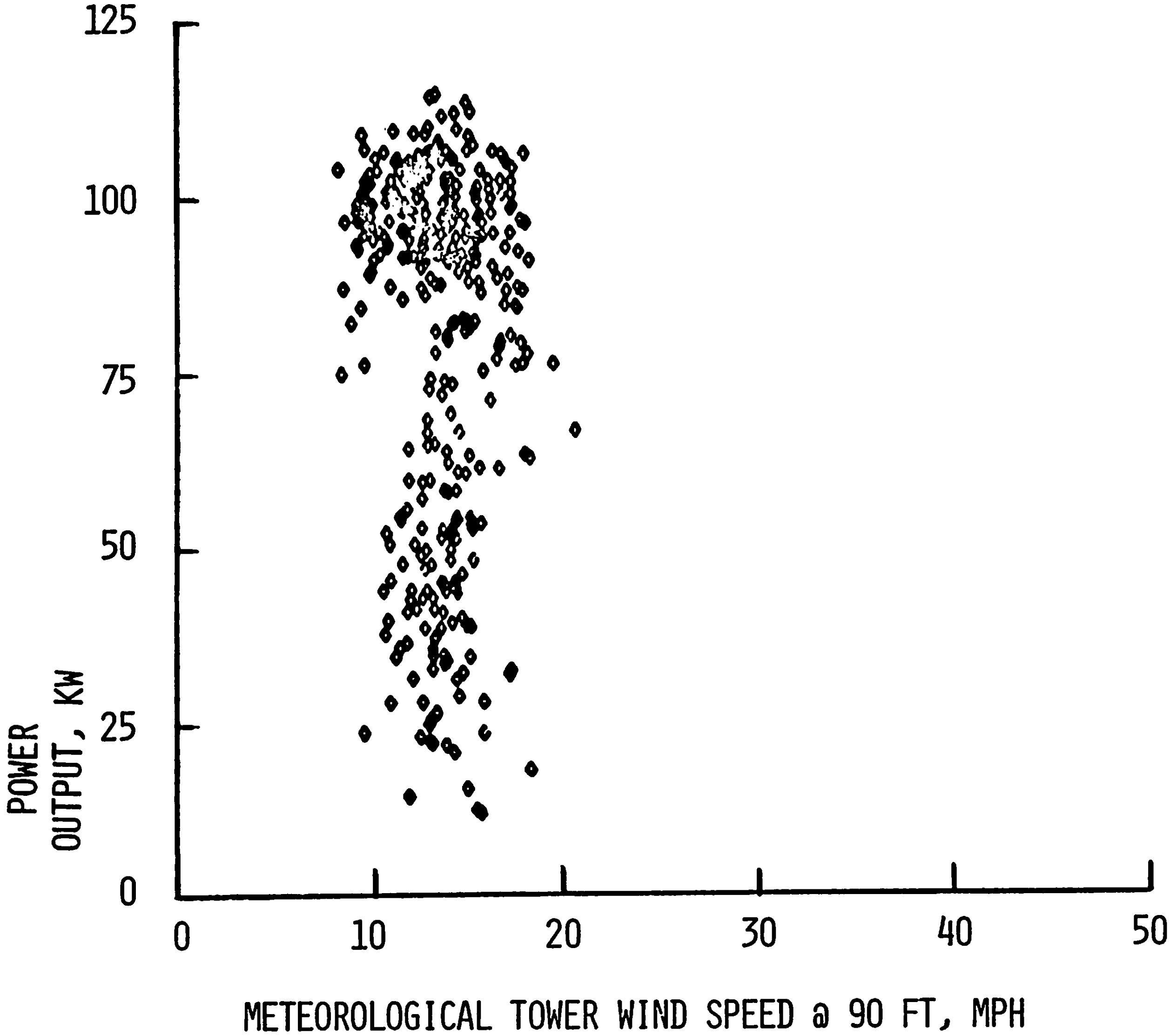
MOD-0 WIND TURBINE AND METEOROLOGICAL TOWER
PLUM BROOK SITE - SANDUSKY, OHIO

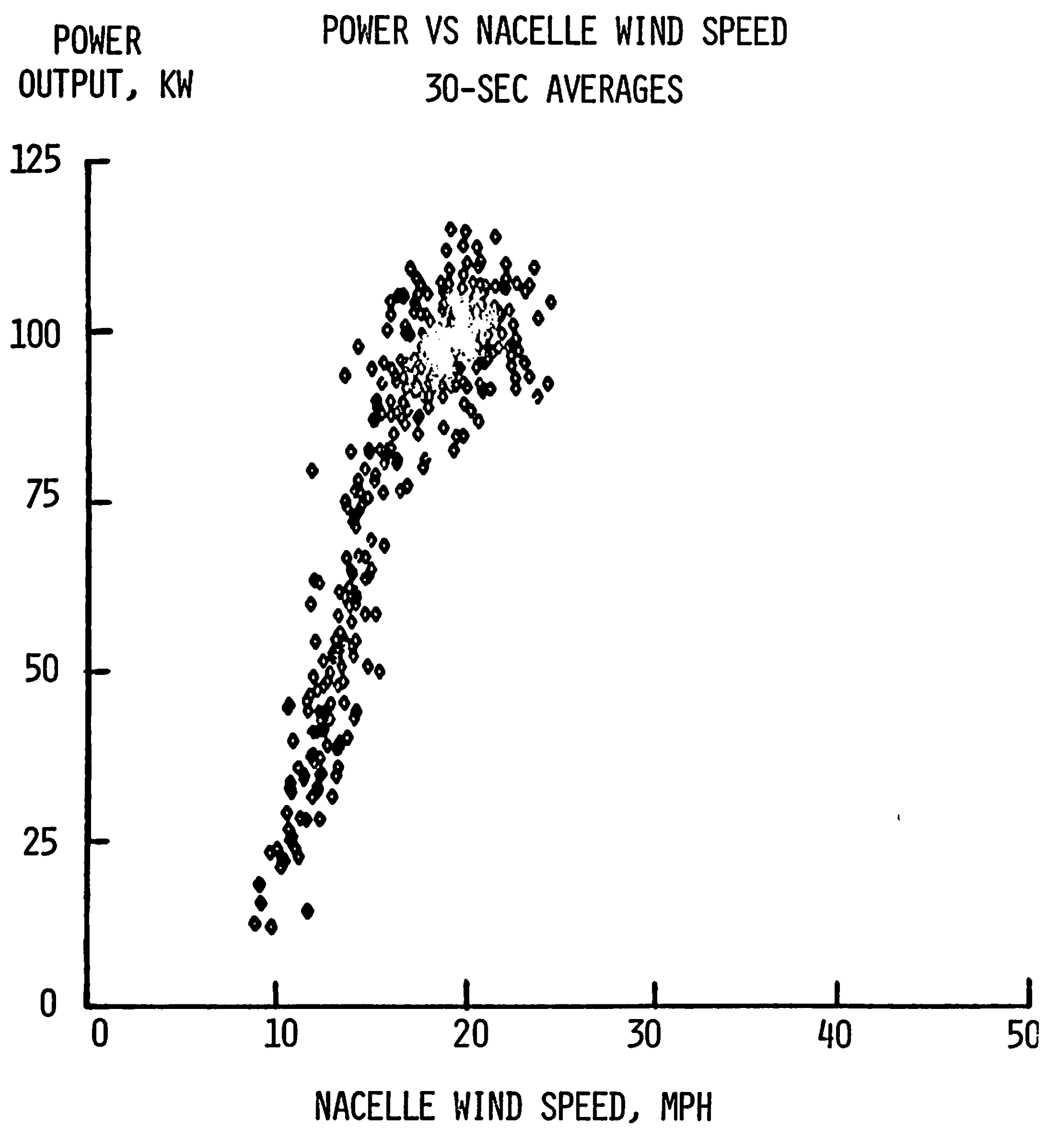
SITE CHARACTERISTICS

TREES, $Z_0 \approx$ .6 FT (.2M)

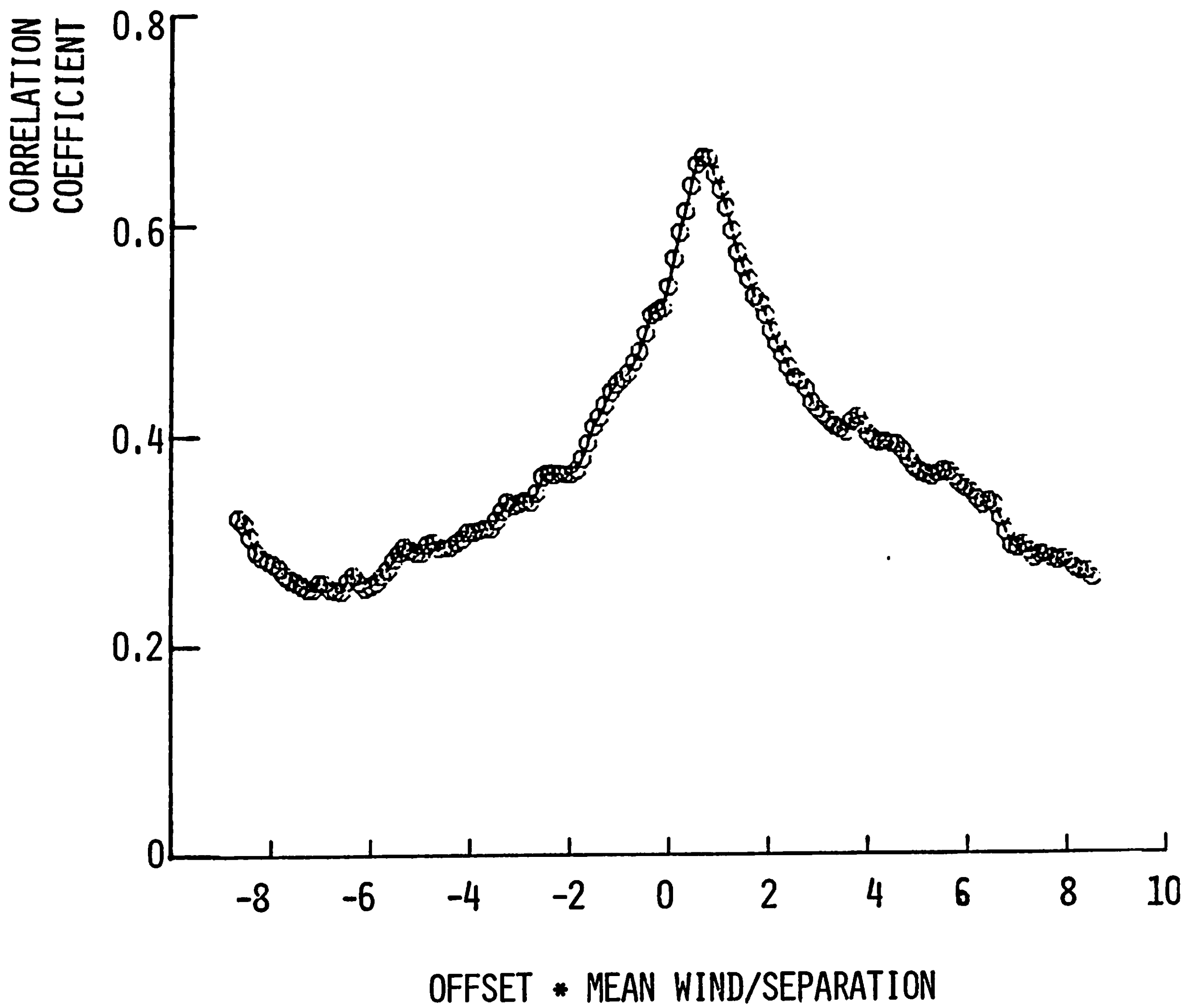


POWER VS METEOROLOGICAL TOWER WIND SPEED @ 90 FT
30-SEC AVERAGES

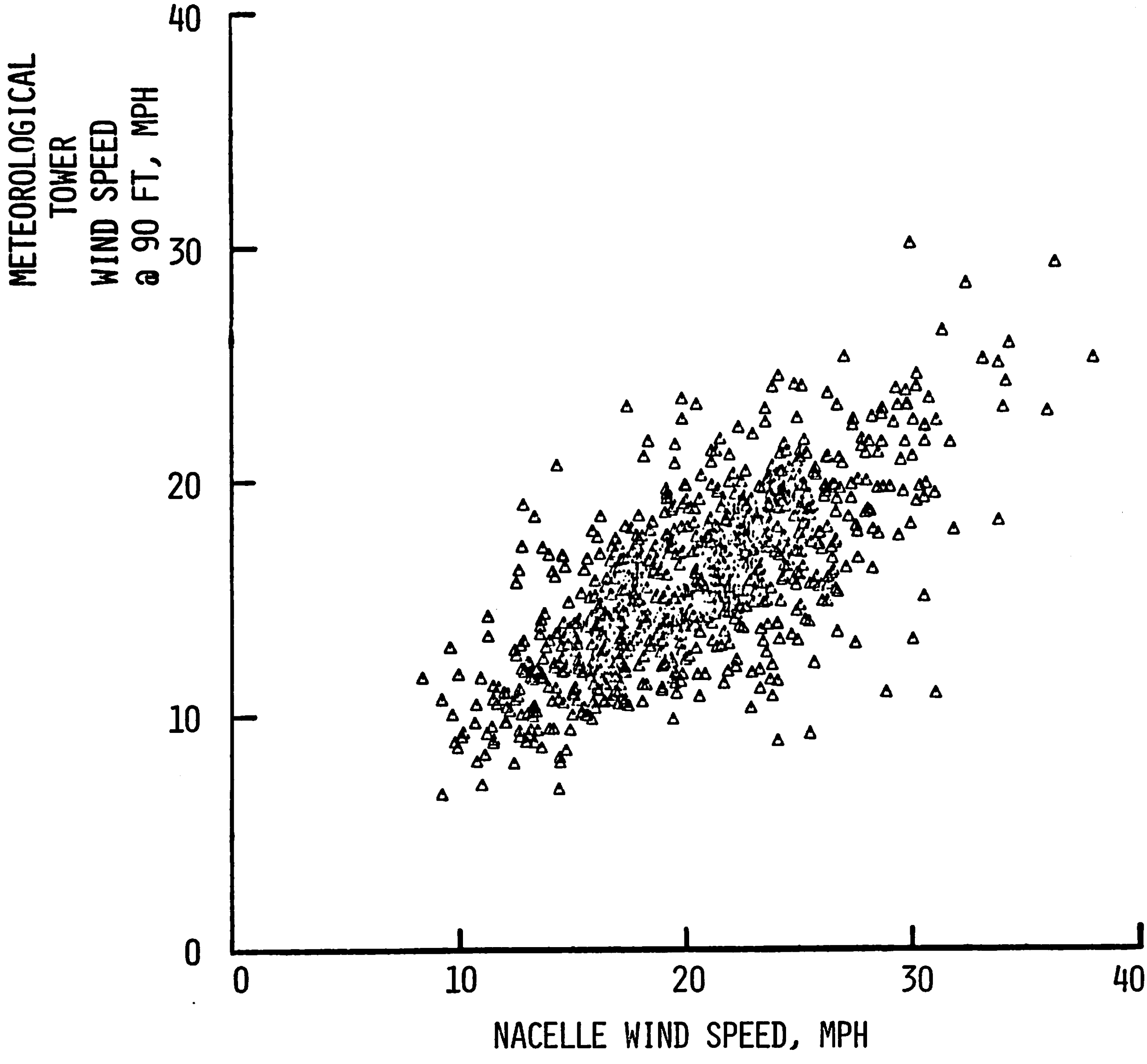


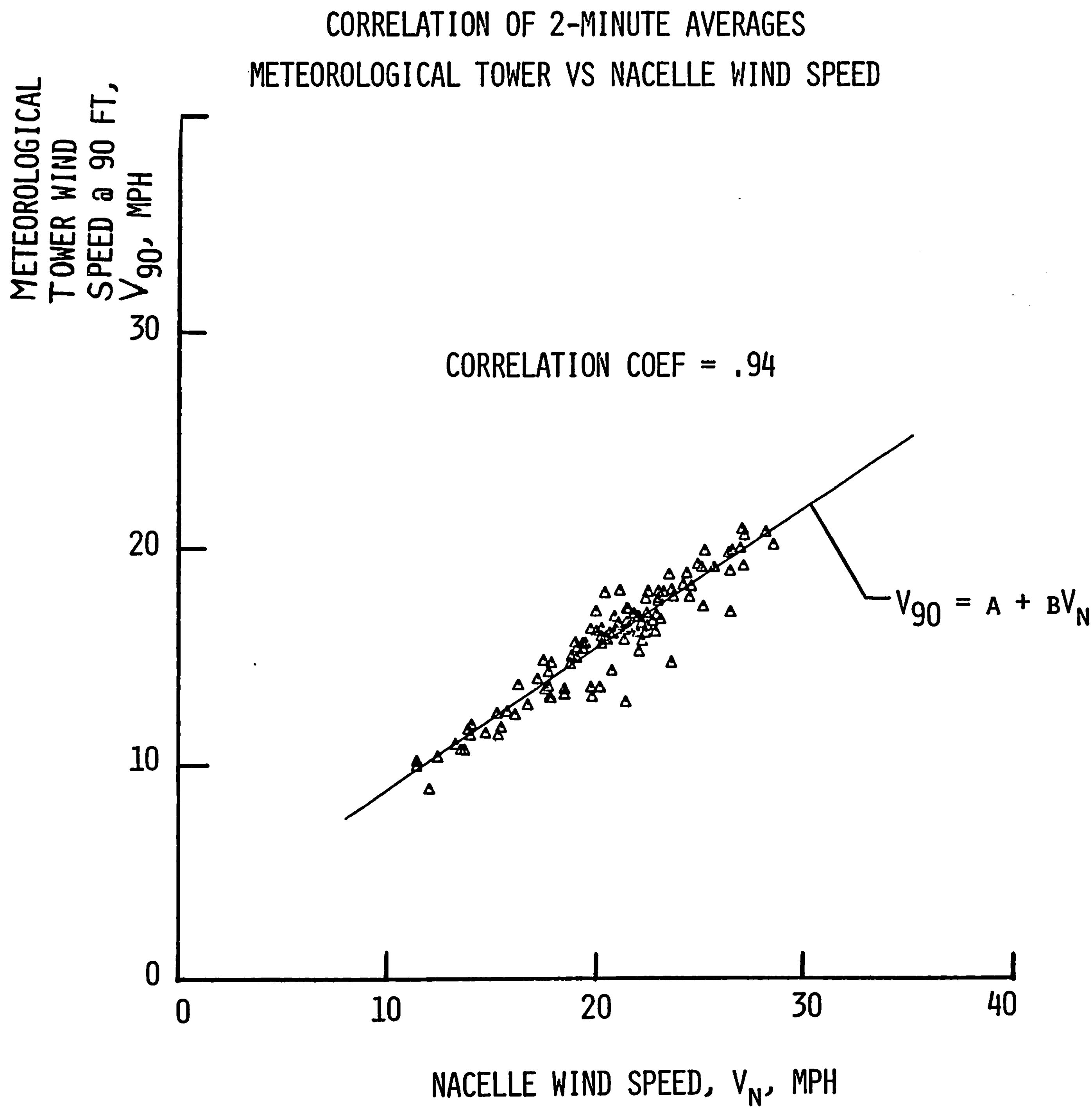

POWER VS NACELLE WIND SPEED
30-SEC AVERAGES
POWER
OUTPUT, KW
125
100
75
50
25
0
0
10
20
30
40
50
NACELLE WIND SPEED, MPH

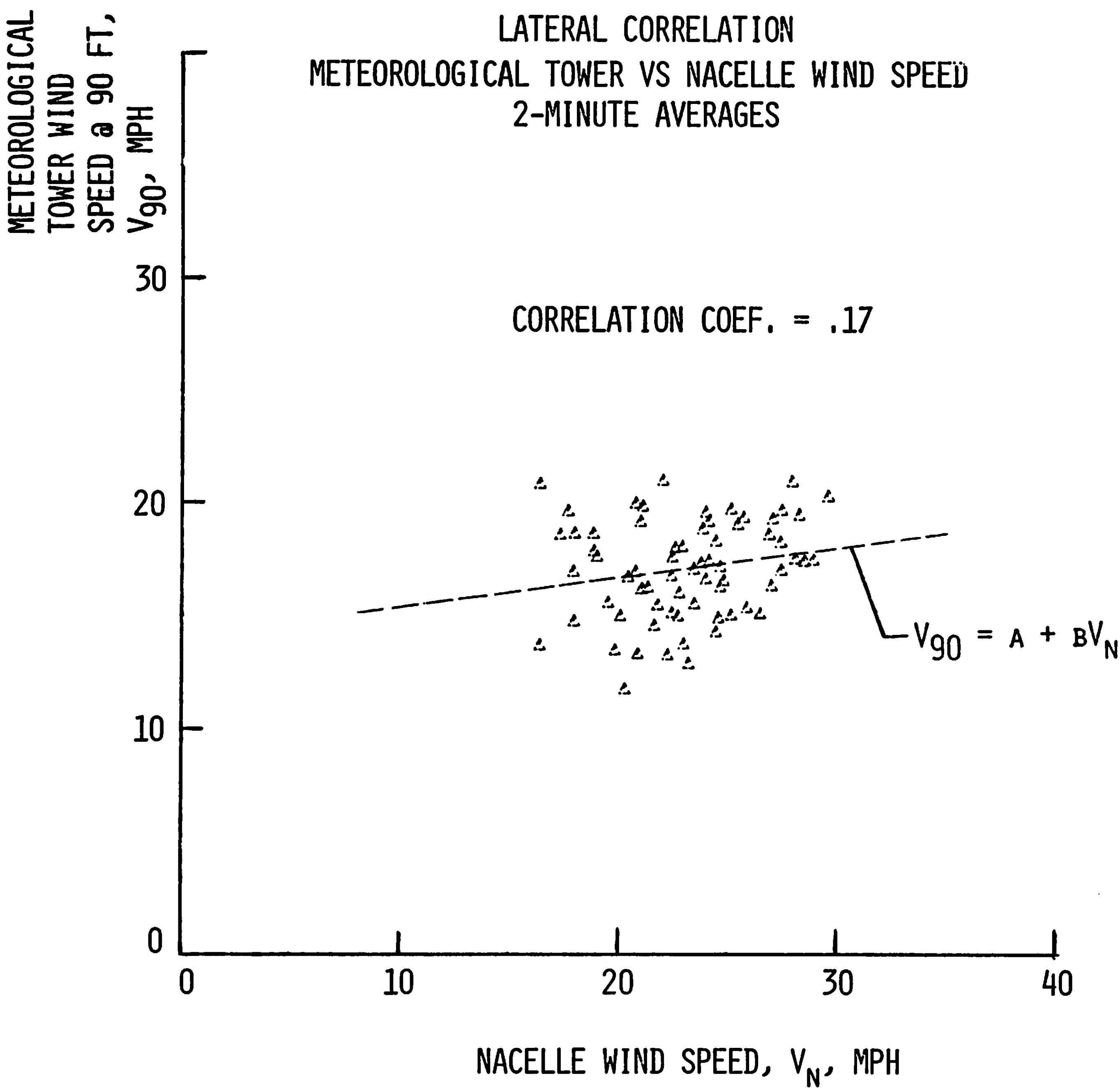
EFFECT OF TRANSPORT TIME ON
CORRELATION OF METEOROLOGICAL TOWER AND NACELLE WIND SPEEDS
WIND TURBINE DOWNWIND OF METEOROLOGICAL TOWER



CORRELATION OF INSTANTANEOUS
METEOROLOGICAL TOWER VS NACELLE WIND SPEED



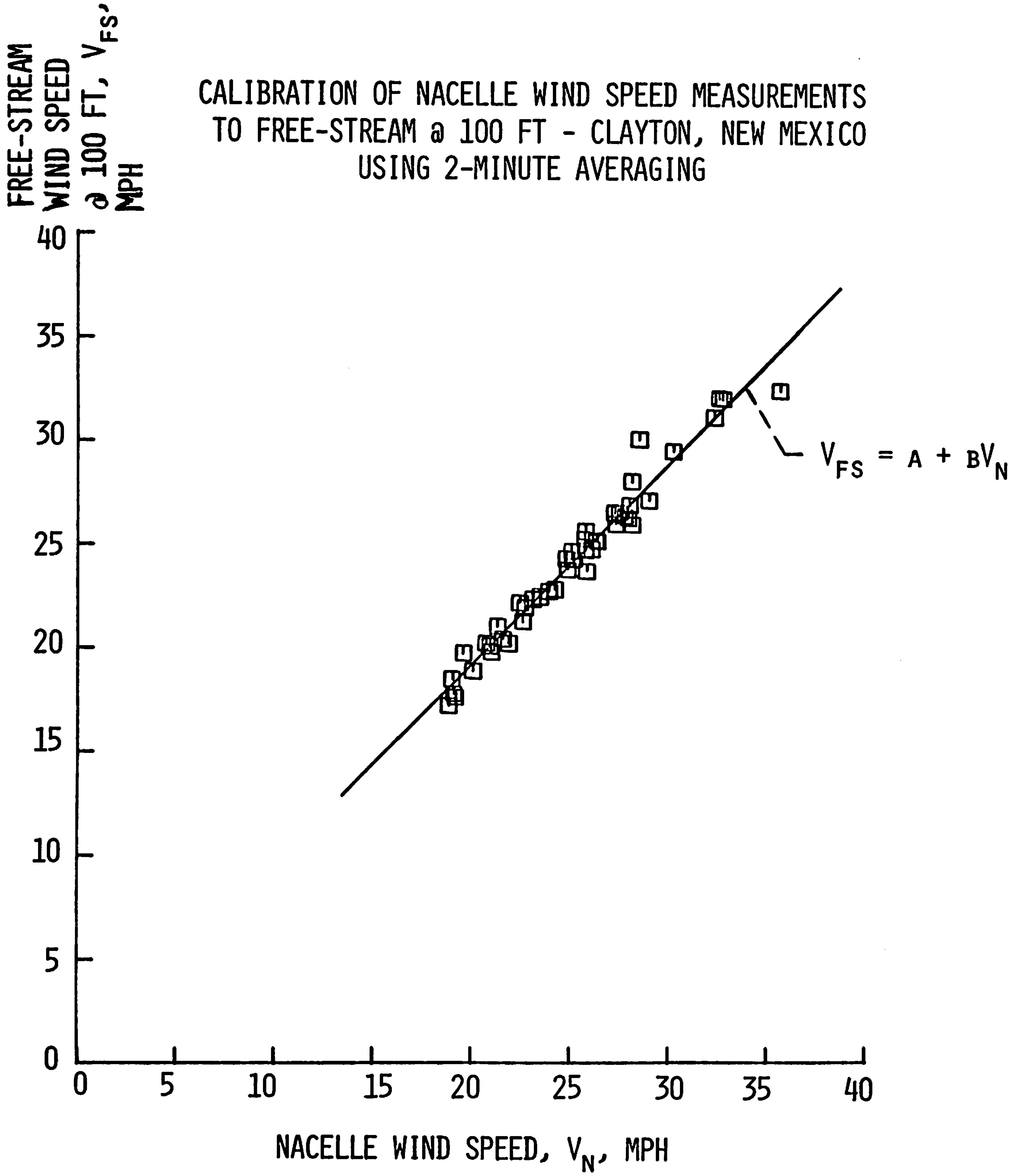

CORRELATION OF 2-MINUTE AVERAGES
METEOROLOGICAL TOWER VS NACELLE WIND SPEED
METEOROLOGICAL TOWER WIND SPEED @ 90 FT, V_{90}, MPH
CORRELATION COEF = .94
$V_{90} = A + BV_N$
0
10
20
30
40
NACELLE WIND SPEED, V_N, MPH



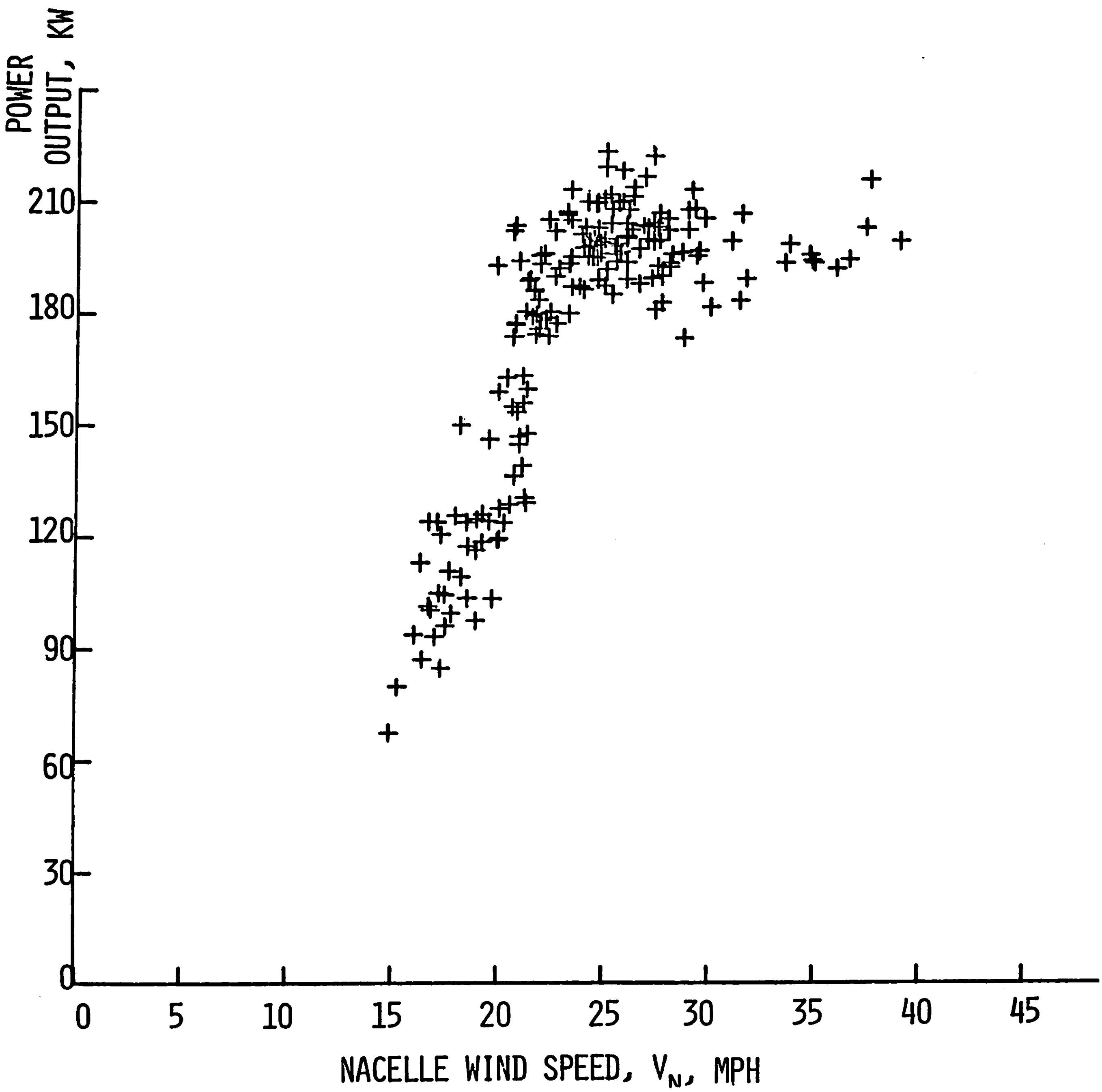
LATERAL CORRELATION
METEOROLOGICAL TOWER VS NACELLE WIND SPEED
2-MINUTE AVERAGES
METEOROLOGICAL TOWER WIND SPEED @ 90 FT, V_{90}, MPH
CORRELATION COEF. = .17
$V_{90} = A + BV_N$
0
10
20
30
40
NACELLE WIND SPEED, V_N, MPH

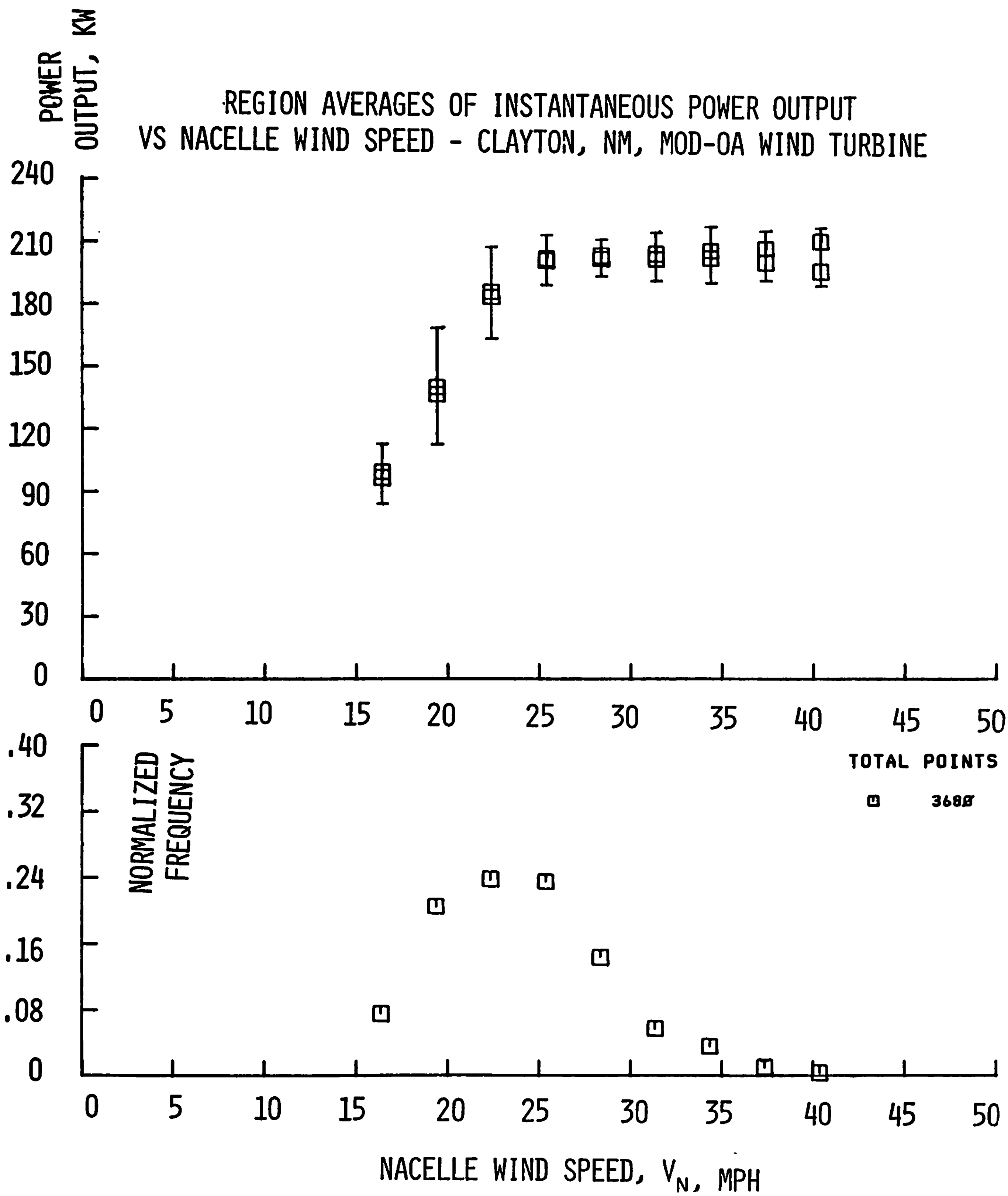
METHOD FOR SHORT-TERM CORRELATION OF POWER OUTPUT WITH FREE STREAM WIND SPEEDS

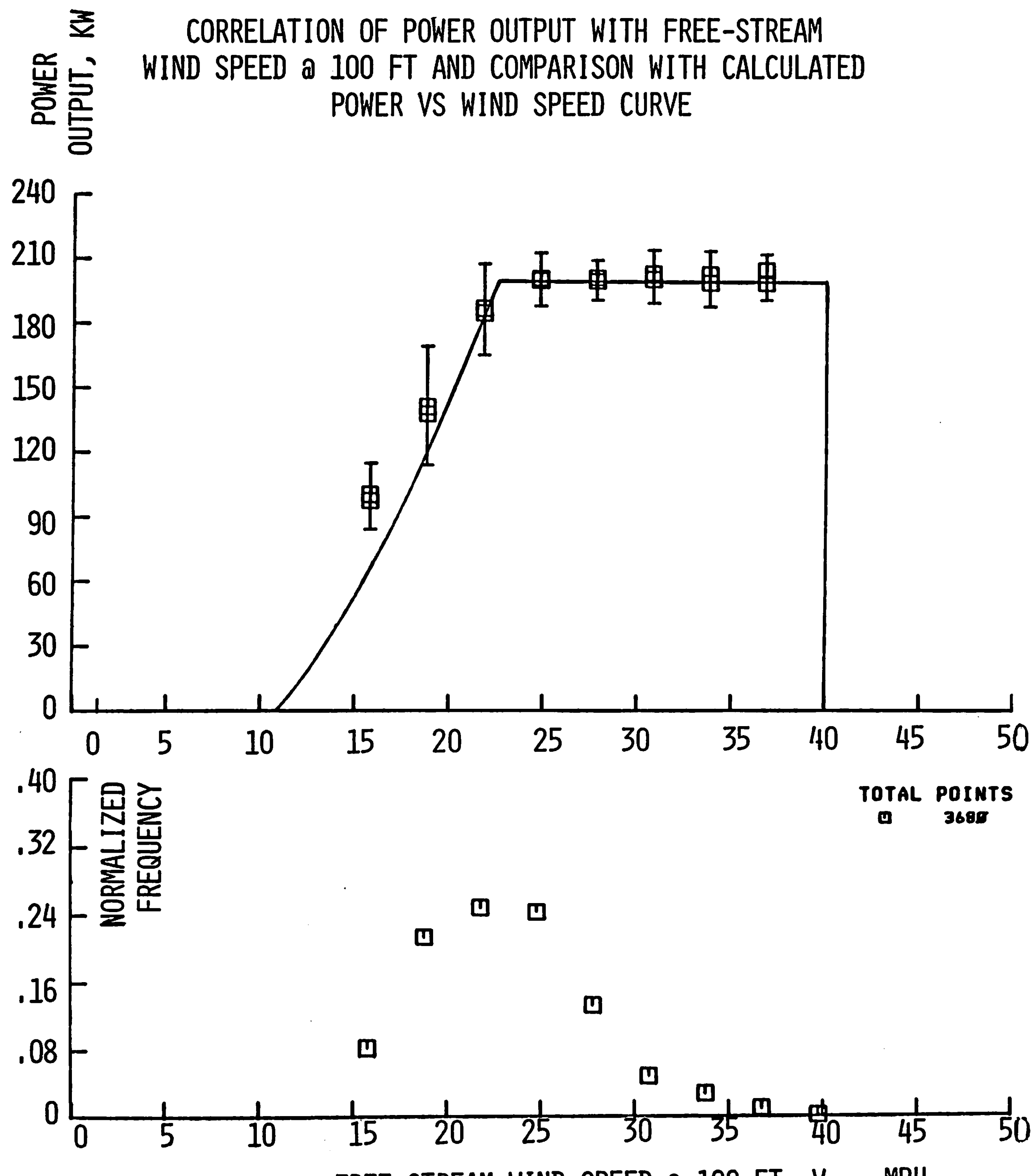
1. SELECT DATA WITH THE WIND TURBINE DOWNWIND OF THE METEOROLOGICAL TOWER.
2. DETERMINE CALIBRATION EQUATION TO CORRECT NACELLE WIND SPEEDS TO FREE-STREAM WIND SPEEDS USING 2-MINUTE AVERAGED DATA.
3. CORRELATE INSTANTANEOUS POWER OUTPUT WITH NACELLE WIND SPEED. ELIMINATE SCATTER USING REGION AVERAGES.
4. USING CALIBRATION EQUATION, CORRECT NACELLE WIND SPEEDS IN POWER VS NACELLE WIND SPEED TO FREE-STREAM.


CALIBRATION OF NACELLE WIND SPEED MEASUREMENTS
TO FREE-STREAM @ 100 FT - CLAYTON, NEW MEXICO
USING 2-MINUTE AVERAGING
FREE-STREAM WIND SPEED @ 100 FT, V_FS, MPH
NACELLE WIND SPEED, V_N, MPH
V_FS = A + BV_N
0
5
10
15
20
25
30
35
40

CORRELATION OF INSTANTANEOUS POWER OUTPUT
WITH NACELLE WIND SPEED - CLAYTON, NM, MOD-OA WIND TURBINE




REGION AVERAGES OF INSTANTANEOUS POWER OUTPUT
VS NACELLE WIND SPEED - CLAYTON, NM, MOD-OA WIND TURBINE
POWER OUTPUT, KW
240
210
180
150
120
90
60
30
0
0 5 10 15 20 25 30 35 40 45 50
NORMALIZED FREQUENCY
.40
.32
.24
.16
.08
0
TOTAL POINTS
3680
0 5 10 15 20 25 30 35 40 45 50
NACELLE WIND SPEED, V_N, MPH


CORRELATION OF POWER OUTPUT WITH FREE-STREAM WIND SPEED @ 100 FT AND COMPARISON WITH CALCULATED POWER VS WIND SPEED CURVE
POWER OUTPUT, KW
240
210
180
150
120
90
60
30
0
0
5
10
15
20
25
30
35
40
45
50
.40
.32
.24
.16
.08
0
NORMALIZED FREQUENCY
TOTAL POINTS
3680
FREE-STREAM WIND SPEED @ 100 FT, V, MPH

MEASUREMENTS FOR LONG-TERM CORRELATION OF POWER OUTPUT WITH FREE-STREAM WIND SPEED

1. ENERGY PRODUCED BY THE WIND TURBINE, KWH
2. TIME SYNCHRONIZED TO THE UTILITY, HRS
3. METEOROLOGICAL WIND SPEED FREQUENCY DISTRIBUTION AT HUB HEIGHT, HRS

AVERAGE POWER OUTPUT WHILE SYNCHRONIZED
NOVEMBER 1978 TO APRIL 1979

MONTH	AVERAGE POWER WHILE SYNCHRONIZED, KW	
	CALCULATED	MEASURED
NOV '78	99	90
DEC '78	110	112
JAN '79[A]	---	90
FEB '79	114	108
MAR '79	115	115
APR '79	118	116
CUMULATIVE AVERAGE	112	108

[A]JANUARY, 1979 WIND DATA NOT AVAILABLE

SUMMARY

1. TWO METHODS (SHORT TERM AND LONG TERM) FOR CORRELATING WIND TURBINE POWER OUTPUT AND FREE-STREAM WIND SPEEDS HAVE BEEN PRESENTED.

2. INSTANTANEOUS CORRELATION OF POWER OUTPUT WITH FREE-STREAM WIND SPEEDS IS ACHIEVED USING THE SHORT-TERM METHOD.

3. LONG-TERM CORRELATION OF MEASURED AND CALCULATED AVERAGE POWER WHILE SYNCHRONIZED IS ACHIEVED USING THE LONG-TERM METHOD.

4. BOTH METHODS SHOW GOOD CORRELATION BETWEEN CALCULATED AND MEASURED PERFORMANCE OF THE CLAYTON, NEW MEXICO MOD-OA WIND TURBINE.

Engineering Assessment of Existing Wind Models for the Design of large WEC's *)

by

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Munich, Germany.

Abstract:

The designer of large WEC's is faced with the fact that the system he designs will be driven from the wind in the height region between 40 and 200 m. The bulk of existing wind data was measured in heights between 8 and 40 m.

The paper gives a survey of existing wind models to be applied to the mentioned operational height region. Critical assessment of the models validity is made and recommended areas for further investigations are identified.

*) To be presented at the IEA Expert Meeting for large Scale Wind Energy Conversion Systems, Blowing Rock, NC, USA, Sept. 26 - 27, 1979.

List of Symbols:

a	:	exponent of Hellmanns law
B, C B*, C*	:	Constants in Maniers law; i.e. $m_P = B + CP$
h	:	height above natural grade
h_i	:	height level i
$\bar{h}$	:	geometric mean height; i.e. $\sqrt{h_1 \cdot h_2}$
k_4	:	turbulence intensity: i.e. $\sigma_{w_\alpha} / \bar{u}(10)$
m_P	:	exponent in Maniers law, i.e. $m_P = B + CP$
$\hat{n}$	:	frequency in Hz
$\hat{n} \frac{h}{\bar{u}(h)}$	:	reduced frequency; i.e. number of cycles (dimensionless)
P(u)	:	probability of wind speed being $\leq$ u
u	:	horizontal wind speed
u (h_i)	:	horizontal wind speed at height h_i
u_P (h_i)	:	wind speed at height h_i, corresponding to probability P
$\bar{u}$ (h_i)	:	mean horizontal wind speed at height h_i
v	:	fluctuating lateral wind speed
w	:	fluctuating vertical wind speed
w_x	:	fluctuating horizontal wind speed; i.e. $w_x = u - \bar{u}$
w_y	:	$w_y = v$
w_z	:	$w_z = w$
w_α	:	fluctuation wind speed along direction α
x	:	coordinate along horizontal mean wind speed

y	:	coordinate lateral to x
z	:	vertical coordinate
z_o	:	surface roughness length
α	:	directional symbol; i.e. $\alpha = x, y, z$
$\eta_{o\alpha}$	:	scaling factor of reduced frequency (dimensionless)
$\sigma_{w\alpha}$	:	standard deviatiation of w_α (RMS value)
$\phi_{w\alpha}(\hat{n})$	:	power spectral density of $w_\alpha \left(\frac{m^2}{sec^2\ Hz}\right)$

1.0 Introduction

Large WEC's are operated in a height region of the atmospheric boundary layer (40 to 200 m) where only limited wind measurement data are available. This is true for both the macroscopie and for the micrometereological wind structure.

The bulk of the wind data at height are derived from deterministic extrapolation algorithms based on measured wind structures at low heights (10 to 40 m typically).

The validity of this approach is limited for the following reasons:

- The wind structure at 10 m reference height is mainly determined by the surface roughness of the adjacent range (1 km upwind typ.) whereas the relevant surface roughness for a height of 100 m and beyond is influenced by a much larger range.

  One-parametric logarithmic or exponential laws for wind speed adjustment for height cannot consider this fact. More-than-one-parametric laws suffer from the lack of verification data for parameter adjustment.

- Wind speed directional changes with height can potentially gain influence.

- Power spectra and cross spectra of the micro-wind structure over the rotor disc area can hardly be extrapolated from low-level measurements. The extrapolation of high-level measurements from measurement locations to the conditions at potential sites must be carefully checked.

A second general concern of the designer is associated with the understandability and usability of data. The designer must be able to understand the influence of metereological phenomena. In order to apply them to the system design the following requirements shall be fulfilled:

- any relationship used shall be described by influencing parameters which the designer is either able to determine from given metereological conditions (e.g. surface roughness, friction speed, heat flux etc.) or - at least - the parameters shall implicitely contain averaged metereological conditions. In the latter case mention shall be made w.r.t. the underlying averaging processes.

- parameter range and/or probability distributions shall be given to allow assessment of sensitivities and error bounds.

- extreme phenomena shall explicitely be described (nature, parameters, frequency) together with their forecast features.

The following sections give an engineering judgement of published wind data material with specific reference to the applicability for the design of large WEC's. Areas of weak and/or conflicting information are identified to stimulate further R & D work.

2.0 Macroscopic Wind Structure

2.1 General

The macroscopic wind structure deals with the statistics of the mean wind. Averaging intervals of 10 min and more shall be assumed.

2.2 Wind Speed at low heights

Data on mean wind speeds measured in anemometer heights of 10 m to 40 m typ. are available for a variety of potential sites (for FRG see e.g. [1], [2]). These data are normally scaled down to a reference height of 10 m. Unfortunately in some publications the original data at measuring height are not given which adds a surplus error to a height adjustment calculation.

2.3 Adjustment of annual mean wind speed with height

Currently Hellmann's formula [3] is used for the calculation of the wind profile over height:

$$\bar{u}\ (h_2) = \bar{u}\ (h_1) \left(\frac{h_2}{h_1}\right)^a \tag{2.1}$$

Unfortunately the exponent a is dependant on the representative surface roughness length z_o, on the height, and on annually averaged thermal stratifications. Roth [4] has shown that for the adiabatic case (neutral stratification) a depends on the ratio

$$\frac{\bar{h}}{z_o}\ ;\ \bar{h} = \sqrt{h_1\ h_2}$$

according zu the following table:

$\bar{h}/z_o$	10	100	1.000	10.000
a	0.43	0.22	0.14	0.11

Unless wind profile measurements at representative sites up to 200 m height over longer periods of time have been performed, the designer is left with the situation that he can choose any annual exponent between 0.12 and 0.18 and even larger ([1], [2]).

The sensitivity to energy output and fatigue load calculations is essential.

2.4 Probability Distribution of Wind Speed and Adjustment with Height

Knowing only the annual mean wind speed at a given height h the easiest way to calculate the probability distribution of u (h) is to use a Rayleigh distribution [5], [6] :

$$(2.2) \qquad P\,[u(h)] = 1 - \exp\left[-\frac{\pi}{4}\left(\frac{u(h)}{\bar{u}(h)}\right)^2\right]$$

(Cumulative Rayleigh Distribution)

According to Wendell and Elderkin [7] the error introduced in annual energy output calculations does not exceed 10% (provided $\bar{u}$ (h) is known within narrow bounds). Still it must be kept in mind that the application of distribution algorithms is only a low-order approximation of the real world.

Especially German authors [1], [2] claim that it is <u>not</u> sufficient to have simular distributions for various heights.

Instead, more complex algorithms have to be applied which consider the fact that low speeds are relatively more attenuated with height than large speeds.

Jurksch [1] and Duensing [2] use an exponential law similar to Hellmann which goes back to Manier [8]. This law allows the calculation of the wind speed distribution at height h_2 from a measured distribution at height h_1:

$$(2.3) \qquad u_P\,(h_2) = u_P\,(h_1)\left(\frac{h_2}{h_1}\right)^m \qquad [8]$$

u_P is the wind speed which corresponds to the probability P in a cumulative wind speed distribution (see fig. 2-1). The different attenuation of different wind speeds is taken care for by a variable exponent m.

Jurksch [1] uses a linear law for m [8] with m dependant on the probability P:

$$(2.4) \qquad m_P = B + CP$$

B and C are functions of the surface roughness and on thermal stratification conditions. By averaging over annual stratification conditions he comes to coefficients:

$$(2,5) \qquad B^* = 0.289$$

$$C^* = -\ 0.080$$

which lead to exponents m between 0.29 and 0.21.

Duensing [2] gave a discribution of m according to fig.2-2, where m depends on wind speed classes.
m according to Duensing lies between 0.20 and 0.125.

Obviously there is a large discrepancy between the authors which calls for clarification and in case further experimental verification.

2.5 Wind speed Profiles with Height for Fatigue Analyses and Catastrophic Failure Assessment

By sweeping the rotor blade over the gradient wind field, the blade experiences periodic wind speed alterations which may achieve amplitudes of 3 m/sec and even more. These alterations will give rise to corresponding changes of the angle of attack and in turn to significant periodic blade loads in-plane and out-of-plane.

In order to perform prel. fatigue analyses it appears sufficient to use Hellmanns law (2.1) with an annualy averaged exponent a. For more detailed analyses the probability distribution of the exponent a shall be known from measured data.

For performance and stress analyses under off-normal conditions extreme wind shear conditions (low level jets, land-sea winds) have to be considered. So far only very limited information [4] is available (see fig. 2-3).

2.6 Horizontal Wind directional Changes with Height

Tuchtenhagen [9] indicates wind directional changes between 50 and 150 m of 3 - 4° at neutral stratification and appr. 10° at stable stratification conditions.

For operational considerations the designer should know both nominal and extreme directional changes with height. Moreover, also the time history of mean wind directional changes is of interest.

2.7 Extreme Wind Speeds

The information on extreme wind speeds compiled by Frost and Turner [5] appears adequate for system design.

3.0 Micrometeorological Wind Structure (Turbulence)

3.1 General

The micrometeorological wind speed (turbulence) shall be assumed to be superimposed on ten-minutes (or more) average wind velocity. Both frequency domain descriptions (power spectra etc.) and time domain descriptions (discrete gust models) are available frome the literature, the most comprehensive paper beeing probably Frost and Turner [5].

3.2 Power Spectra

The "nominal" wind speed fluctuations are described by power spectral desities ϕ_{w_α} where w_α stands for the fluctuating components of the wind speed:

$$
\begin{aligned}
w_x(t) &= u(t) - \bar{u} \\
w_y(t) &= v(t) \qquad (3.1) \\
w_z(t) &= w(t)
\end{aligned}
$$

Power spectra, normalized to the relevant variances $\sigma^2_{w_\alpha}$, are given in fig. 3-1 [5].

The corresponding turbulence intensities $\frac{\sigma_{w_\alpha}}{\bar{u}(10)}$ can be determined from fig. 3-2 [5] as a function of z_o and height.

Fig. 3-2 indicates that the turbulence intensity decreases with height (being appr. 0.2 for 50 m height and 0.18 for 100 m height for z_o = 0.1). Taking into account that also the coherence in lateral direction decreases with the dimension of the rotor disc, it appears that the excitation of system modes from wind speed fluctuations is relatively less severe for large WEC's than for small WEC's.

Nevertheless verification data at WEC's heights supporting the relevance of the data presented in [5] are needed.

3.3 Cross Spectra, Coherence:

In order to perform wing response calculations [10], cross spectra of u (or alternatively coherence and phase spectra) in lateral direction (y and z-separation) over the dimensions of the rotor disc shall be available. It appears that a number of obervations by various investigators have been performed already, which need to be compiled for engineering use. Furthermore additional measurements over larger separations at WEC's heights shall be performed.

3.4 Extreme Gust

Extreme longitudinal gusts cannot be assessed from the power spectral densities (fig. 3-1) due to their rare occurance. Frost and Turner [5] have given formulae and curves for a determination of gust shape and amplitude as a function of height and gust period. Gust periods in turn can be assessed from the spatial distance over which the gust is 50 percent coherent.

Obviously only positive longitudinal gusts are considered in [5]. Potentially even more severe for a down-stream-WEC are negative extreme gusts, imposed on mean wind speed. An indication about their existence and, in case, order of magnitude is requested for catastrophic failure assessment.

4.0 Wind Direction

Information on wind direction probability and fluctuations, sufficient for design purposes, is contained in [5].

5.0 Recommendations for Future Measurement Programs

Since obviously the wind structure up to a height of 200 m is not known within the required accuracy, both for normal and off-normal conditions, a measurement program is proposed according to the following requirements:

- location : representative for WEC's use, preferably at WEC's site
- max. measurement height : 200 m
- vertical separation steps : appr. 20 m
- lateral separation steps (at hub height) : $\leq$ 20 m
- measuring equipment : to be compatible with the requirement to determine simultaneously the macroscopic and the microscopic wind structure together with their driving forces (thermal stratification)
- frequency range for micro wind structure measurement : 0,01 Hz - 0,1 Hz - 1 Hz
- measurement period : $\geq$ 1 year
- required information :
  - annual mean wind speed with height (wind speed profiles)
  - distribution (frequency of occurrence) of mean wind speed profiles

- extreme shear winds
- extreme wind speeds during measurement period
- wind speed distributions for different heights
- power spectra/turbulence intensities with height
- cross spectra in z and y direction
- extreme gusts during measurement period
- directional changes of 10-min mean wind speeds with height
- directional rate of change of 10-min mean wind speeds
- wind speed directional fluctuations.

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DOE CANDIDATE SITE METEOROLOGICAL MEASUREMENT PROGRAM[(a)]

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INTRODUCTION

A primary goal of the U.S. Department of Energy (DOE) is the rapid commercialization of wind energy. One way that DOE is achieving this goal is by installing prototype wind turbines on sites proposed by electric service organizations. The utilities field test and operate these turbines for a period of several years and use the electricity produced by the turbines in their electrical network. The NASA-Lewis Research Center (NASA-Lewis), which manages the design, construction, and installation of the turbines (which range in size from 200 kW up to 2.5 MW or larger) also coordinates the field testing activities.

In March of 1976, DOE issued an RFP to acquire, on a competitive basis, a group of candidate sites, proposed by utilities interested in the field testing program. Meteorological measuring equipment would be installed by DOE on these candidate sites to assess the wind energy potential at the site. As prototype machines reach a stage of development where an installation site is needed, a site would be chosen competitively from among these candidate sites.

A total of 17 candidate sites were selected from the 64 proposals submitted in response to the RFP (see Figure 1). From these sites, five have been chosen thus far to receive turbines for field testing (these are indicated in Figure 1). This paper discusses the meteorological measurement activities at these sites and provides details of the measurement program as it exists in late 1979. In addition, the paper briefly discusses the directions this program will take in the near future, and the options interested electric service organizations have for participating in the program.

(a) This paper was based on work preformed under U.S. Department of Energy Contract No. EY-76-C-06-1830.

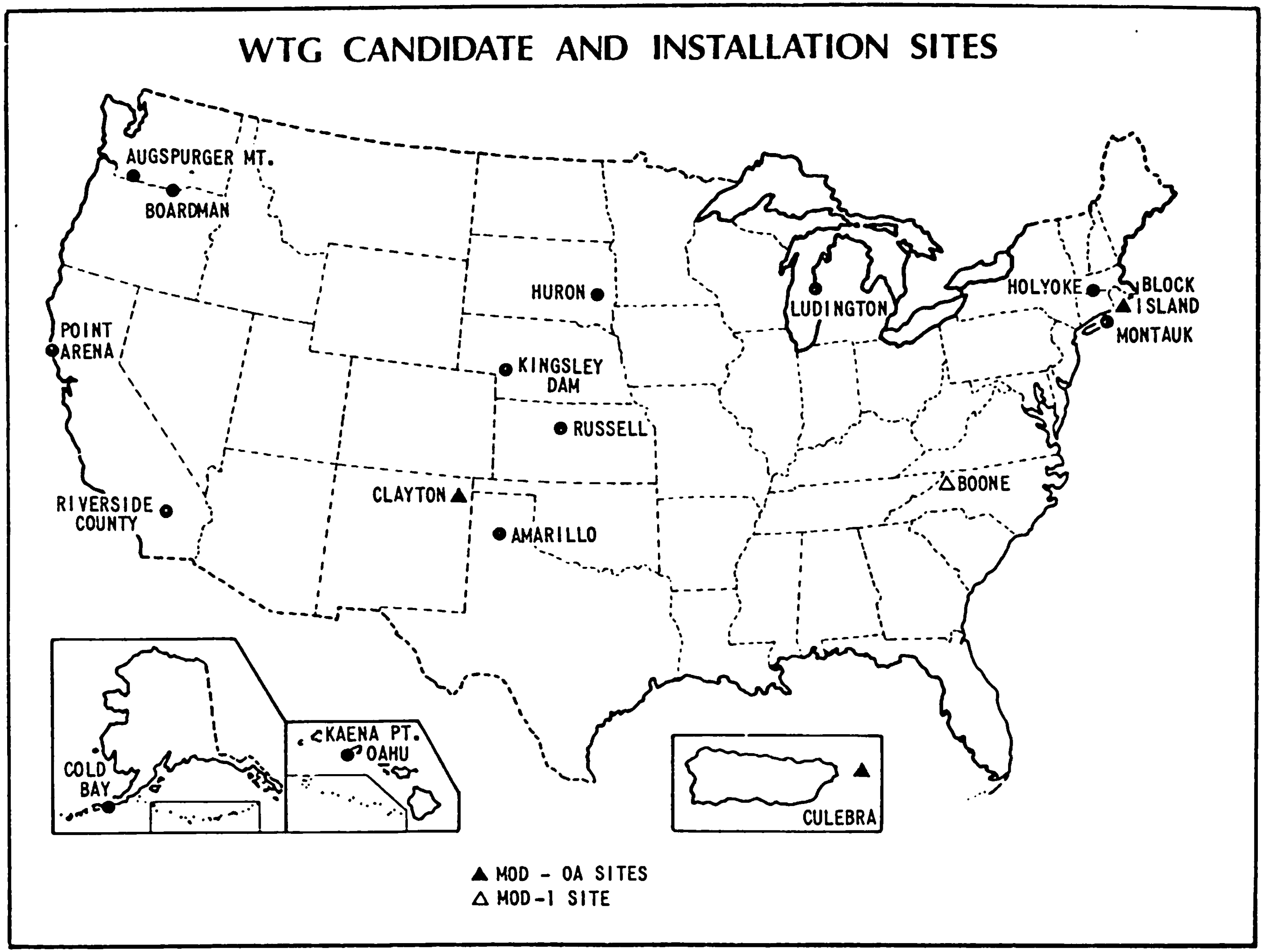

FIGURE 1. Seventeen Candidate Sites Selected in 1976

METEOROLOGICAL VALIDATION PROGRAM

THE FIRST TWO YEARS

The process of obtaining meteorological measurements at candidate wind turbine sites has become known as the Meteorological Validation Program (MVP). NASA-Lewis selected Western Scientific Services, Inc. (WSSI) of Ft. Collins, Colorado as its meteorological measurement contractor. As the meteorological measurement contractor, WSSI provided services in installing and maintaining the meteorological equipment and in analyzing and publishing the data. After the 17 sites were selected, WSSI arranged for the installation of 150-ft Rohn 55 G meteorological towers and for the placement of MRI 1074 cup and vane anemometers at two levels on these towers. The data from the sensors were recorded on strip chart recorders - each sensor having its own recorder. At most sites, the sensors were installed at the 30-ft and 150-ft levels. At some sites the lower level was chosen to be 60 feet to avoid effects on the measurements as a result of nearby obstructions. At all sites, the tower was installed at a location about 100 meters from where a wind turbine would actually be located.

The towers were generally located upwind, in the prevailing wind direction, of the turbine location. The purpose of this arrangement was to ensure that the tower would measure the free-stream wind characteristics so that the data could be used for performance evaluation of the turbine if the site were selected to receive one. Table 1 provides information on the measurements at these sites during this phase of the program. As noted in the table, some utilities supplied their own meteorological systems, while others made their own towers available to the program.

Upon receiving the strip charts from the utilities each month, WSSI arranged to have the data reduced by hand and summarized into hourly wind speed and directions. WSSI also prepared monthly data reports. Because these 17 sites were involved in a competitive arrangement for receiving the first generation of wind turbines (totaling four 200-kW MOD-OAs and one 2000-kW MOD-1), the distribution of the data reports was limited to DOE, NASA-Lewis, and Pacific Northwest Laboratory (PNL).

TABLE 1. Pertinent Information About the 17 Candidate Sites for Period December 1976 - September 1978

Name of Site	Utility	Instrument Levels, m	Start of Measurements
Amarillo, TX	Southwestern Public Service	9.1, 45.7	March 1977
Augspurger Mt., WA	Bonneville Power Administration		December 1976[a]
Block Island, RI	Block Island Power Company	9.1, 45.7	December 1976
Boone, NC	Blue Ridge Electric	18.2, 45.7	December 1976
Clayton, NM	City of Clayton	9.1, 45.7	May 1977
Cold Bay, AK	Alaska Bussell Electric Company	9.1, 21.8[b]	August 1977
Culebra, PR	Puerto Rico Water Resources Authority	9.1, 45.7	March 1977
Holyoke, MA	Holyoke Gas and Electric	18.2, 45.7	December 1976
Huron, SD	East River	9.1, 45.7	December 1976
Kingsley Dam, NB	Central Nebraska Pub. Power and Irri. Dis.	9.1, 45.7	December 1976
Ludington, MI	Consumers Powers	18.2, 45.7	April 1977
Montauk, Long Is., NY	Long Island Lighting Company	18.2, 45.7	January 1977
Point Arena, CA	Pacific Gas and Electric Company	9.1, 45.7	January 1977
Russell, KS	City of Russell	9.1, 45.7	December 1976
San Gorgonio Pass, CA	Southern California Edison	9.1, 45.7	December 1976
Boardman, OR	Portland General Electric	9.1, 39.6, 70.1[c]	January 1977[d]
Kaena Pt., HI	Hawaiian Electric Company	9.1, 45.7[c]	December 1976

(a) Measurements terminated in January 1978
(b) Tower supplied by utility
(c) Meteorological equipment, data reports supplied by utility
(d) Data collected by the utility since 1974

CURRENT MEASUREMENT ACTIVITIES

In 1978, PNL in Richland, Washington, operated by Battelle Memorial Institute, assumed the responsibility of the MVP from NASA-Lewis. PNL selected as its subcontractor Environmental Systems Corporation of Knoxville, Tennesse, to provide calibration, maintenance, and data reduction services at the candidate sites. Although at this time there were a total of 16 candidate sites (measurments were terminated at Bonneville Power Administration's Augspurger Mountain site in January 1978 because of severe winter icing conditions), ESC was responsible for maintenance of 14. The other two sites, Kaena Point (Hawaiian Electric Company) and Boardman (Portland General Electric) were maintained by the proposing utilities (see Table 1).

In the fall of 1978 ESC traveled to each of the 14 sites and installed instrument elevators and ESC CD7-700A digital cassette data loggers on the towers. In some cases the strip chart recorders were retained as back-up systems. The primary system of recording wind speed and direction is presently the digital data loggers, which record instantaneous samples every two minutes.

A goal of 90% data recovery at each site has been established for this program. Achieving this can be challenging since unlike other programs with similar goals, there are generally no back-up systems at the sites, and often the sensors and logger are checked only once a week by utility personnel. In general, data recovery decreased during the winter months when severe weather hampered performance of the sensors and loggers.

Since the late fall of 1978, the following procedures have been observed to produce monthly data reports from each of the 14 sites.

Data Editing and Reduction

Every two weeks a representative of the utility visits the tower site, changes the cassette tape in the data logger, and mails the data-filled cassette to PNL's subcontractor. The utility representative also visually inspects the tower and sensors, checks the performance of the logger, and fills out a site inspection form, which is also mailed to the subcontractor.

The voltage data on the cassette data tapes are then converted to engineering units and transferred to a nine-track tape. The data are then edited to note spurious values with the aid of a computer-assisted data editing program as well as by the visual inspection of a meteorologist. A final, edited nine-track tape is then prepared, and a copy mailed to PNL for use in preparation of a monthly data report.

Data Reporting

When a monthly nine-track data tape is received at PNL, it is put into various data analysis programs, which provide summaries of pertinent wind characteristics at each candidate site. These summaries are incorporated into monthly data reports, which are forwarded to NASA-Lewis, DOE, and each participating utility to allow an assessment of the wind energy potential at the sites. These monthly reports include such information as mean and standard deviations of wind speed and direction, joint wind speed and direction frequencies, mean hourly wind speeds, cumulative frequency distribution of wind speed, wind speed persistence, maximum gusts, turbulent intensities and power law coefficients, as well as a log of the sensor performance during the period.

Calibration and Maintenance

The subcontractor provides routine calibration and maintenance services, as well as emergency maintenance services, at each of the 14 sites. For example, when a utility representative reports a sensor or logger failure, the subcontractor proceeds to the site within 72 hours to correct the problem (in some instances, the problem can be identified and corrective procedures implemented by discussing the situation with the utility representative over the telephone).

The subcontractor also performs periodic calibrations at each of the sites. Annually, calibrations include changing all sensors with precalibrated spares. Quarterly onsite calibrations of all electronics are performed. The precalibrated wind speed sensors have been calibrated in a wind tunnel (ESC uses the HTDL wind tunnel at the Oak Ridge National Laboratory; WSSI utilizes the Colorado State University wind tunnel facilities). All calibrations are traceable to standards established by the National Bureau of Standards.

Quality Assurance

A Quality Assurance (QA) program, similar to that required by the Nuclear Regulatory Commission, has been established for the MVP. The objectives of the QA program are to ensure that all procedures for calibration, maintenance, and data reduction are carefully documented. The QA program requires, for example, that the engineering units created from the data tapes are accurate conversions from the sensor output voltage values recorded on the tapes. A key element of the QA program is the filing of Nonconformance Reports, which document the apparent time and type of any component failure and the steps taken to remedy the situation.

PNL's subcontractor is required to designate a QA officer who ensures that all QA procedures are strictly followed. The QA officer is not directly associated with the calibration, maintenance, and data reduction activities and therefore retains a more independent, unbiased perspective of the program.

Turbine Installation Sites

Of the 16 candidate sites in the current program, five have been selected to receive large wind turbines for field testing. These five sites, which are indicated in Figure 1, are:

Site	Turbine
Clayton, NM	MOD-OA (rated at 200 kWe)
Culebra, PR	MOD-OA
Block Island, RI	MOD-OA
Boone, NC	MOD-01 (rated at 2 MWe)
Oahu, HI	MOD-OA

Special modifications to the meteorological measurement program have been made at these turbine sites. At the operational MOD-OA sites (this includes Clayton, Block Island, and Culebra) a third level of sensors has been installed on the towers at the 100-ft level (hub-height). In addition, the MRI sensors have been replaced with more sensitive climet 011-3 wind speed and 012-15 wind direction sensors. This allows for more detailed turbulence studies at these sites when the loggers are operated at their high-speed data collection rate (one sample every 1.5 seconds). This sampling rate is utilized periodically for research purposes.

Another important feature at these sites is that turbine output parameters (alternator power output, nacelle yaw error, and wind speed and direction from the nacelle anemometer) are being recorded simultaneously with the meteorological tower data. This allows detailed analysis of the turbine's performance and response to the meteorological conditions at the site.

At the Boone, North Carolina site the tower was extended to 290 ft so that a Federal Aviation Administration (FAA) warning light could be installed (the MOD-1 blade tip is 275 ft above the ground). A third level of sensors was installed at the 275-ft level on the tower. Arrangements have not been made to record turbine output parameters on the data logger at this time.

The original MOD-OA site at Kaena Point on the island of Oahu, Hawaii, has been moved to the Kahuku area. No meteorological tower exists at the Kahuku site at present, but when all approvals have been made for construction of the turbine, a 150-ft free-standing tower will be installed about 60 m north of the wind turbine. The tower will be equipped with three levels of sensors and a digital cassette data logger similar to those at the other MOD-OA sites.

FUTURE CANDIDATE SITES

In the summer of 1979, DOE announced two Program Opportunity Notices (PONs) to all electric service organizations in the United States. The first PON was to select from interested electric service organizations about 20 sites for installation of meteorological towers. Some of these sites, which meet specific requirements for the MOD-2 2500-kWe wind turbine installation, are to be designated as MOD-2 candidate sites, while the remaining are to be designated as candidate sites for future wind turbine systems. The second PON was to select the MOD-2 installation site from the MOD-2 candidate sites.

Meteorological towers similar to the existing candidate sites will be installed at these new candidate sites in the spring of 1980. All sites will have three levels of climet wind sensors, but otherwise the configuration will be the same as at the existing sites. The present sites can remain in the program as candidate sites for the next generation of machines.

Interested utilities that did not respond to the PON within the designated deadlines can enter into candidate site agreements with DOE in the future by submitting unsolicited proposals and by offering to install meteorological equipment similar to that installed through the DOE program. The exact nature of this meteorological equipment is specified in the PON. The proposals will be evaluated for their merit before a formal agreement is established.

At the time of this writing, nearly three years of data have been collected at most of the 17 candidate sites selected by DOE in 1976. About one year of this data is 2-min digital data recorded on magnetic tape. DOE plans to continue measurements at these sites for at least one more year, and to install meteorological scanning equipment at approximately 20 new sites in the spring of 1980. Measurements at these new sites will be conducted for at least two years.

IEA EXPERT MEETING ON LS-WEC'S

September 26-27, 1979

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