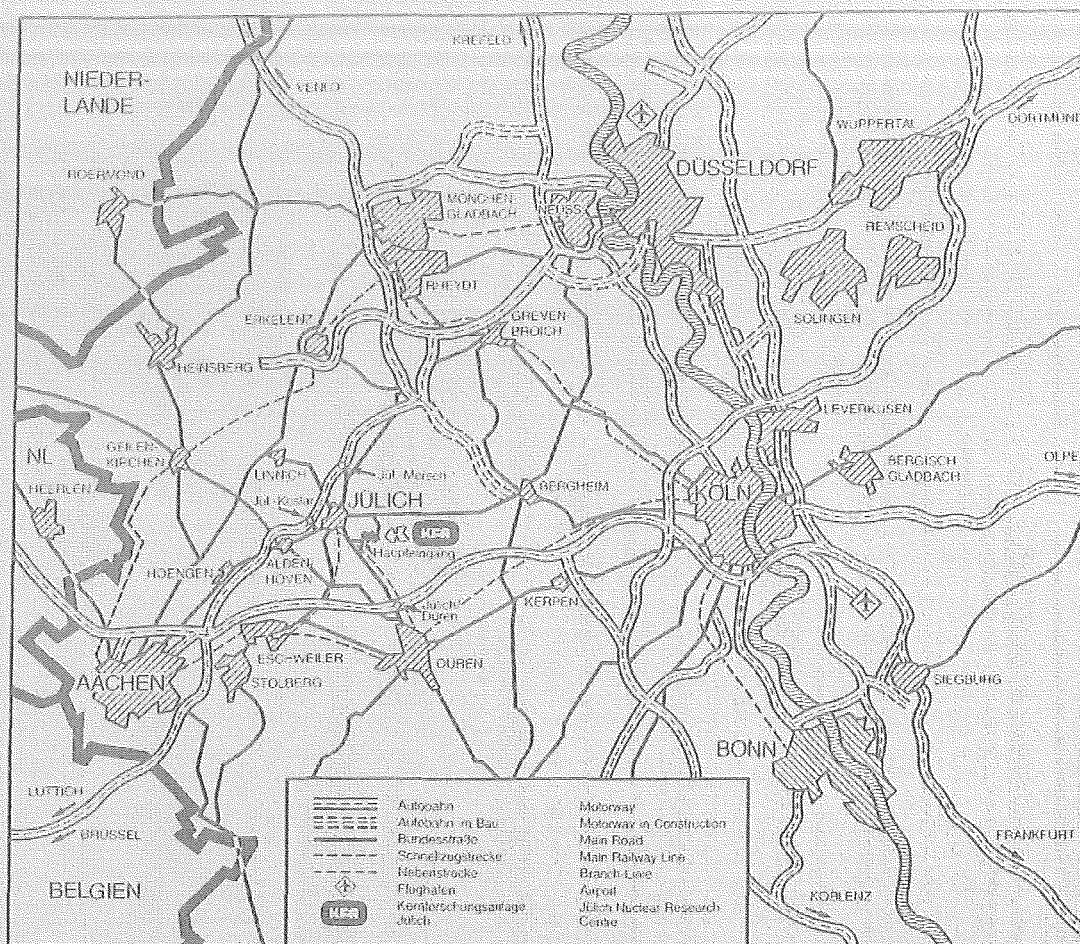# KERNFORSCHUNGSANLAGE JÜLICH GmbH

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

11th Meeting of Experts – General Environmental Aspects
of Large Scale Wind Energy Utilization

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 and
the Fluid Mechanics Department
of the Technical University of Denmark.

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

11th Meeting of Experts – General Environmental Aspects of Large Scale Wind Energy Utilization

Munich, May 7-9, 1984

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 and
the Fluid Mechanics Department
of the Technical University of Denmark.

Scientific Coordination:
A. Gustafsson (Aeronautical Research Institute, Sweden)
M. Petersen (Techn. Univ. of Denmark)
S. Engström (Aeronautical Research Institute, Sweden)
R. Windheim (PLE-KFA Jülich)
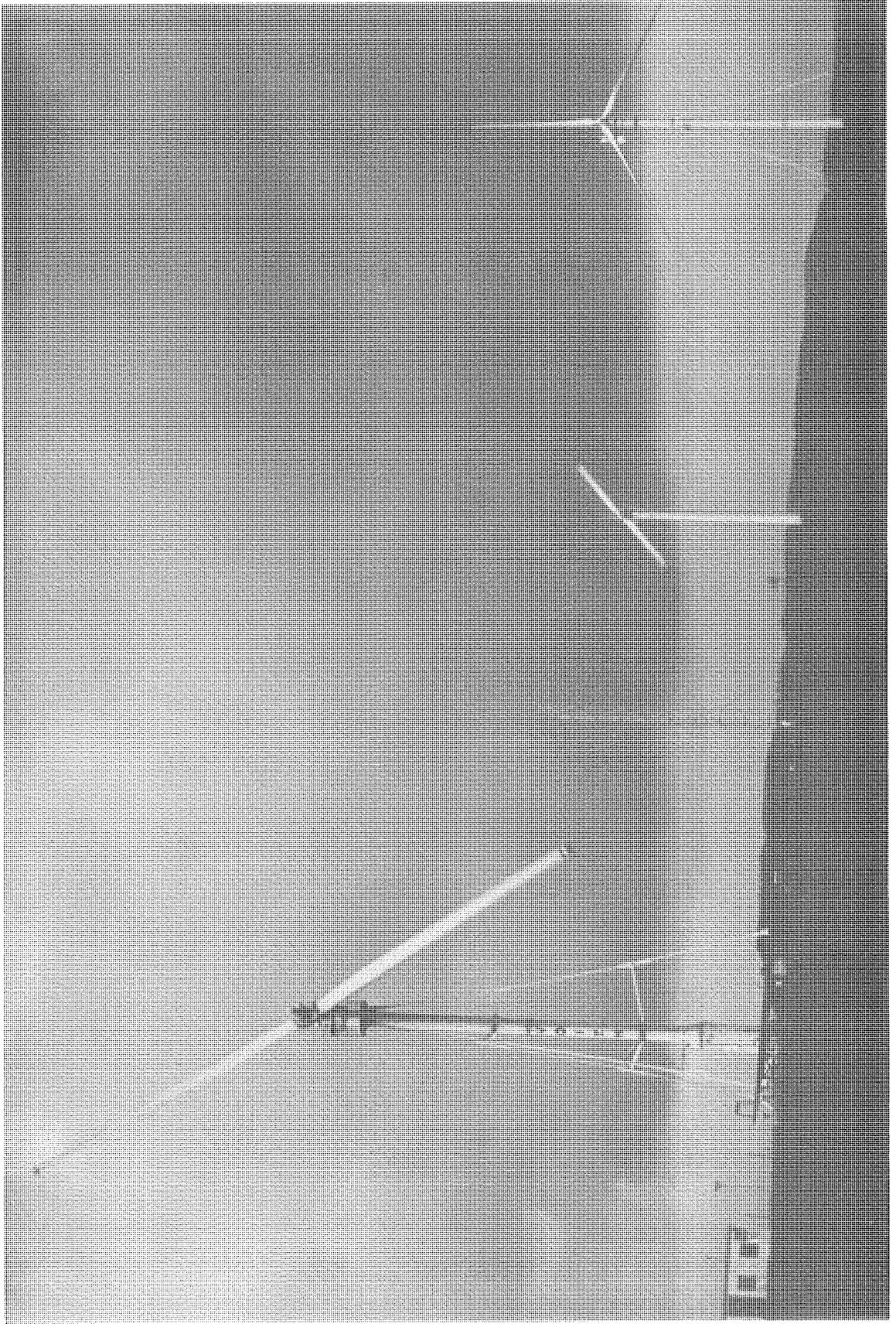
Wind test facility Stötten, July 16, 1984:

Left: 270 kW Voith turbine

Middle: 20 kW Aeroman on the DFVLR test platform

Right: 30/100 kW DEBRA turbine

Tobe erected 84/85: - OPTIWA research unite

                    - Single blade turbine FLAIR

C O N T E N T S

GENERAL ENVIRONMENTAL ASPECTS ON

LARGE SCALE WIND ENERGY UTILIZATION

by

Staffan Engström

National Energy Administration

and

Anders Gustafsson

Aeronautical Research Institute

1.   Introduction

The number of megawatt-scale wind turbines in the world
is still around ten, with an accumulated operation ex-
perience of probably less than 10 000 hours. The best
performing units have passed 2 000 hours. This is to
compare with the situation with small wind turbines
between 20 and 100 kW, where many thousand of units are
installed and the accumulated experience accounts to
millions of hours. In the 100-1000 kW region the number
of machines is still in the region of some tens, but
the operation experience is longer than for the mega-
watt scale range, partly due to the US Mod OA program.

2. Safety issues

Obviously there is a possibility that objects such as
ice or fractured parts may leave the blades of a wind
turbine and that this could cause damage to humans and
property. Several examples of blades or parts of blades
leaving wind turbines have been told. It ought however
to be pointed out that the maximal consequences of such
an accident are rather limited. Nevertheless the problem
has to be properly considered.

Hence attempts have been made by different authors to
investigate maximum and probable area around a wind
turbine where hit is possible. Using throw dynamics,
aerodynamics and statistics the probability to be hit
by a thrown object can be determined. One important
question which has to be answered when defining a safety
distance is hence what level of risk to be hit that can
be accepted. Another basic question is if the probabil-
ity of throwing an object can be kept low enough by
technical devices, such as crack detection etc.

Throw distance calculations

Early calculations based on particle dynamics indicated
throw distances of less than 250 m. More recent calcula-
tions including blade aerodynamics (blade flying, thumb-
ling and wiggling) and skidding on the ground indicated
possible distances of up to 700 m. Due to the drag the
maximum distances for ice shedding is more limited.

Evaluating the probability to be hit in a certain point
in the surrounding of a turbine the following statistical
considerations have to be made:
- where does the break occur (radius, azimuth angle
  pitch angle)
- wind direction and speed
- ground impact behavior (fragment size, angle at
  impact, speed, friction)

Several of the basic assumptions in these calculations
need further scrutiny as many parameters have great un-
certainties. However different authors have independent-
ly arrived at similar results.

If the great possible throw distances indicated by cal-
culations are reliable this underlines the importance
of minimizing the blad failure probability.

Suggested actions:

- Make systematic analyses of known experiences of
  thrown blades or parts of blades to verify throw
  calculations.

- Investigate and develop further different technical
  means to minimize the risk of a blade failure such
  as crack detection devices etc.

Questions:

- Are there any known cases of injuries or damage on
  the ground due to thrown objects incl. ice?

- Even if maximum throw distances may be great in same
  cases, the probability of being hit is so low that
  it does not seem to change the overall risk. Com-
  pare with airplane crashes, where a very small pro-
  portion of the casualties occur among those not
  travelling in the plane. Is it worthwhile to further
  develop and verify the analysis methods? Is safety
  a limitation for siting of wind turbines?

3. Noise

Broad band audible noise

Consists of blade noise, blade wake noise and noise from
machinery i.e. gear box. The design of blade tips, brake
devices and surface joints is also of importance.

This type of noise is depending on design parameters
mainly rpm and produced power but also turbine diameter,
number of blades and blade chord.

Questions:

- Are the broad band noise levels from today´s machines
  satisfactorily, or are measures required to decrease
  the emission?

- Should some designs be favoured because of broad-band
  noise, e.g. three-bladed machines (lower rpm) or
  variable speed machines (low rpm at low wind speeds,
  when background noise is lowest)?

Low frequency noise/infrasound

The experiences of low frequency noise from the MOD 1 initiated extensive work on prediction methods and means to minimize this type of noise. This also initiated some scepticism about downwind machines.

The emission of low-frequency impulsive noise is depending on several design parameters like:
- wake velocity decrement behind the tower, which is depending on distance from tower, tower size and form
- turbine rpm and diameter
- eventual vortex shedding from tower

A typical feature of the low-frequency noise is that it propagates over far greater distances than the broadband noise. The propagation is also depending on weather and terrain.

Questions:

- Is the low-frequency problem for downwind machines properly documented or is it still mostly speculations?

- Are we within the wind energy community doing enough work to investigate and solve this problem?

- Has the low-frequency problem been overemphasized?

Noise regulations:

Existing noise regulations for industrial installations do not take background wind noise into account. The regulations also do not deal with the low-frequency problem. It is important to point out the special character of wind turbine noise in comparison to other noise sources. When there is no wind there is in principle no noise from wind turbines. It should however also be pointed out that due to atmospheric wind shear there may be very little wind on the ground when a big machine is operating and generating noise.

Regulating authorities have to be convinced that existing regulations must be supplemented for background wind noise and for low frequencies to be applicable for wind turbine installations.

Suggested actions:

- Initiate serious and extensive noise measurements
  for different types of machines within the IEA com-
  munity. Follow the IEA recommended practices for
  WECS testing, the noise part of this is just
  finished.

- Improve and develop measurement technique especially
  for background wind noise.

- Validate theoretical prediction tools and hence de-
  pendence on design parameters.

These steps could be stimulated through information ex-
change within IEA (i.e. expert meetings and task sharing
work). The goal should be to show how WECS noise emission
can be minimized through technical development and hence
fulfill noise regulations at close enough distances.

4. TV-interference

The possibility that WECS can cause interference to
electromagnetic communications has been realised for
some years. Most attention has been paid to TV-inter-
ference but there is a potential to interfere with any
form of electromagnetic signal. Practical experiences
of the problem has now been made in some countries
although the circumstancies vary. The phenomena is similar
to what is experienced by other tall structures but
when the wind turbine operates the interference is fluct-
uating which can be particularly annoying.

It has been suggested that locations of WECS within
100 m - 1 km from the line of sight between microwave
communication links have to be avoided. Areas close to
transmitting stations require special care.

Important aspects are the possibility to predict the
effects of new installations. Measurements and documen-
tation of effects at existing machines is important
for this.

Despite the fact that the circumstancies vary from country
to country it should be of great importance that we share
our different experiences about importance, costs and
any legal aspects.

Prediction of effects of new installations

The prediction of TV-interference effects depend on a

number of more or less well known parameters such as:

- size, design and material of the tower
- size, design and material of the blade
- position of relevant transmitters
- strength, polarisation, coding, frequency of signals
- local topography

Only the first two parameters are dependent on the WECS and all the others are site dependent. Hence measurements at one site is not likely applicable to any other site.

TV-interference is most likely in areas where there is a weak signal due to the distance from the transmitter, where existing reception is poor because of surrounding hills and where the WECS is exposed in a good position to receive and scatter interfering signals.

Measurements of effects of existing machines

The measurement of effects of existing machines would serve two possible purposes. First it would enable verification of theoretical estimates and hence increase knowledge. Secondly it is necessary to determine whether or not disturbance was being caused by the WECS. To be able to really verify this measurements must be performed even before installation of the WECS.

Questions:

- Do we have indications enough to state that any particular design or blade material causes less disturbances than others?

- Is cable-TV or a special local slave transmitter the only solutions? Are the costs for this acceptable for a wind farm installation?

- There is a trend towards future distribution of TV via cable. Does it imply that TV I will be no problem in the future?

5. Visual impact

Wind energy utilization may be very benign environmentally. However, wind turbines are large objects and the visual impact will always exist. The "visual pollution" has been raised as a major disadvantage in some cases, even enough to ask for a ban in some areas. On the other

hand, so far nobody seems to have complained about the
appearance of e.g. the Swedish large WECS; in contrary
many have found them less disturbing than anticipated
and even said that they are beautiful.

The critics often attack the windfarm approach:
"a forest of windmills". And indeed the combination
of very close siting (down to a few diameters distance
from turbine to turbine) and small turbines tend to
give that impression, e.g. in some Californian wind-
farms. Large wind turbines may be more acceptable if
the group appears more like a number of individual units
than like a forest.

Questions:

-   The same energy output can be achieved with either
    a large number of small units or a small number of
    large ones. Is the latter alternative mor acceptable
    from a visual viewpoint? What about the view of roads
    and power lines as compared with the wind turbines?

-   Should the turbines be arranged in a strict order
    or is it preferable to put them "haphazardly", e.g.
    where the conflict with farming is minimal.

6. Impact on farming etc.

A large WECS will need some land around the tower for
permanent use (parking etc). Something like 2000 m^2 per
tower seems likely. A permanent fence is not necessary.
Some land will also be needed for roads and power lines.
Net land use per unit seems to amount to about 3000 m^2
for a typical Swedish case. This does not raise a severe
conflict with farming interest even where the land is
very productive. However, there may be emotional problems
- "why should I sell this little piece of land, the
small money means nothing to me, I will only have dis-
advantages from it". There is also the problems with
the right of the wind, which at least in theory should
belong to the landowner according to Swedish law, but
the wind so far has been looked upon as something which
is free. When wind energy becomes profitable - i.e. when
a wind power installation gets a higher value than the
cost to install it - this may change. A key to future
installations may then be to get the landowner and
others in the community economically involved in the
project.

In order to minimize the conflict with farming, the units
should preferably be sited on spots of non-productive

land where such exist, close to existing roads and
power lines and in such a manner that they influence
as little as possible on the manner of farming.

Question:

- Are there any examples of farming interest making
  it impossible to install large wind turbines?

7. Bird life

Very few examples are known of birds having hit the
wind turbine or its tower. There seems to be no differ-
ence between the danger of a wind turbine and any other
tall structure. In those cases where birds have crashed
into tall structures, common factors seem to have been
bad visibility, low cloud ceiling, bad light conditions
and a possibility of being misled by lights on the
structure.

Most birds have a very short life expectancy due to
natural causes. Normally a few extra casualties will not
influence the bird population. However, when it comes
to endangered species, even single deaths may not be
acceptable.

Questions:

- Are there any new examples of bird deaths due to
  wind turbines?

- Is possible bird kill a major problem even in areas
  with high bird density?

- Migrating birds often have very distinct tracks.
  A case is known when a new and very long bridge
  changed the migration pattern. Is it possible that
  a cluster of windmills can do the same, or are the
  birds likely to travel between and above the wind-
  mills?

CALCULATION OF TRAJECTORIES OF DETACHED
WIND TURBINE BLADES AND PREDICTION OF SITE
RISK LEVELS ASSOCIATED WITH FAILURES OF HAWT'S

by

Jens Nørkær Sørensen
Department of Fluid Mechanics
Technical University of Denmark

0. ABSTRACT

For the prediction of trajectories of detached wind turbine
blades, the governing equations of the full motion, which
includes both translation and rotation of the blade, are derived.

The aerodynamic forces and moments, acting on the blade, are
determined by use of strip-theory and constructed airfoil data,
which take into account, that the blade can be exposed to all
possible angles of the relative free stream velocity.

A study of the sensitivity of trajectories and throw distances
to changes in the conditions, by which the blade is detached,
is carried out.

Finally a statistical model is presented, by which the damage
to people, under assumption of detachment of a blade/blade-
fragment, can be determined. The results are shown for a 2 MW,
60 m diameter HAWT.

1. INTRODUCTION

As part of the wind power program of the Ministry of Energy
and the Electric Utilities in Denmark, an investigation of the
risk of being hit by a blade or part of a blade, has been car-
ried out (Sørensen [11], [12] and [13]).

In the present paper the main results of this investigation
will be presented.

In previous investigations (Pedersen et.al. [8]) trajectories
and by this throw distances were calculated by use of a balli-
stic model, where the drag coefficient was kept constant and

lift forces were ignored.

In the following a refined model, which take into account the full 3-dimensional motion of a detached blade under influence of gravity and aerodynamic forces, will be presented, and main results of the calculated trajectories will be shown.
The calculated trajectories give the basis for calculations of site risk levels.

For the prediction of site risk levels, a statistical model, which gives the probability for a person being hit by a blade/ blade-fragment, will be presented.

Results will be shown for a blade of the so-called Project K wind-turbine, which is presently under design.

2. CO-ORDINATE SYSTEMS AND TRANSFORMATIONS

To describe the rotation and translation of a body in space, it is necessary to define an inertial co-ordinate system and a body co-ordinate system, and a connection between the two systems must be derived.

2.1 Co-ordinate systems

For the description of the spatial path of the detached wing we define a global inertial co-ordinate system $(0,x,y,z)$.
This system, shown on fig.1a, has its Origo on the ground and its y-axis oriented in the wind direction, its z-axis oriented in the direction of the tower axis and its x-axis perpendicular to these latter. To the co-ordinate system is related the ortho- normal basis $(\underline{i},\underline{j},\underline{k})$.
On the wing is located a body axis system whose Origo is the center of gravity G . The axis of the body system (x^*,y^*,z^*) are identical to the principal axis of the wing. All variables given in this co-ordinate system are denoted with superscript "*". To the body axis system is related the orthonormal basis $(\underline{b}_1,\underline{b}_2,\underline{b}_3)$ (fig.1b), which rotate and translate with the wing. By choosing the body axis identical to the principal direc- tions, it is possible to treat the translation and rotation of the wing independent of each other.

The components of the basis vectors $\underline{b}_i$ are given by the following notation:

$$\underline{b}_1 = (b_{11}, b_{12}, b_{13})^T$$

$$\underline{b}_2 = (b_{21}, b_{22}, b_{23})^T \qquad (2.1)$$

$$\underline{b}_3 = (b_{31}, b_{32}, b_{33})^T$$

2.2 Co-ordinate transformation

The basis vectors of the body co-ordinate system are given in the inertial co-ordinate system as follows:

$$\begin{Bmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{Bmatrix} = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{Bmatrix} \underline{i} \\ \underline{j} \\ \underline{k} \end{Bmatrix} = [B] \begin{Bmatrix} \underline{i} \\ \underline{j} \\ \underline{k} \end{Bmatrix} \qquad (2.2)$$

The matrix $[B]$ determines the orientation of the wing, and it gives the transformation from body co-ordinates to global co-ordinates. Defining orientation by triads of vectors ensures uniqueness for arbitrary rotation of the wing. This is in opposition to the application of the 3 Euler angles, which are not unique in all cases.

3. EQUATIONS OF MOTION

As mentioned above, the total motion is separated in two motions, namely a translation caused by the influence of gravity and aerodynamic forces, and a rotation caused by the aerodynamic moments acting about the center of gravity.

3.1 Equations of translation

By use of Newton's 2. law, the equations of translation can immediately be written as follows:

$$\ddot{x}_G = F_x/m$$

$$\ddot{y}_G = F_y/m \qquad (3.1)$$

$$\ddot{z}_G = F_z/m - g$$

where m denotes the mass of the wing, (x_G, y_G, z_G) are the

position vector of the center of gravity, F_x, F_y and F_z are the aerodynamic forces acting on the center of gravity, and g denotes the acceleration of gravity.

3.2 Equations of rotation

The rotation of the wing is expressed by use of the Euler equations of motion:

$$I_x \, \dot{\omega}_x^* + (I_z - I_y)\omega_x^* = M_x^*$$

$$I_y \, \dot{\omega}_y^* + (I_x - I_z)\omega_y^* = M_y^* \qquad (3.2)$$

$$I_z \, \dot{\omega}_z^* + (I_y - I_x)\omega_z^* = M_z^*$$

where $\underline{\omega}^* = (\omega_x^*, \, \omega_y^*, \, \omega_z^*)$ is the vector of rotational velocity around the center of gravity, I_x, I_y and I_z are the principal mass moments of inertia and M_x^*, M_y^* and M_z^* are the aerodynamic moments acting around the center of gravity.

It must be pointed out, that all the variables appearing in eq.(3.2) are given in body co-ordinates. By use of the transformation matrix [B] , we obtain the following relation between the rotational velocity in body co-ordinates $\underline{\omega}^*$ and the rotational velocity in global co-ordinates $\underline{\omega}$:

$$\underline{\omega} = [B]^{-1} \, \underline{\omega}^* \qquad (3.3)$$

or, using vector notation for $[B]^{-1}$ and dissolve $\underline{\omega}^*$ in its components, we get:

$$\underline{\omega} = \omega_x^* \, \underline{b}_1 + \omega_y^* \, \underline{b}_2 + \omega_z^* \, \underline{b}_3 \qquad . \qquad (3.4)$$

In general the relation between $\underline{\omega}$, $\underline{b}_i$ and $\dot{\underline{b}}_i$ is given as:

$$\dot{\underline{b}}_i = \underline{\omega} \times \underline{b}_i \qquad , \quad i = 1,2,3 \qquad (3.5)$$

Inserting eq.(3.4) into eq.(3.5), we get the following relation:

$$\begin{Bmatrix} \dot{\underline{b}}_1 \\ \dot{\underline{b}}_2 \\ \dot{\underline{b}}_3 \end{Bmatrix} = \begin{bmatrix} 0 & \omega^*_z & -\omega^*_y \\ -\omega^*_z & 0 & \omega^*_x \\ \omega^*_y & -\omega^*_x & 0 \end{bmatrix} \begin{Bmatrix} \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{Bmatrix} \qquad (3.6)$$

Now, the complete motion of the wing is described by the equations (3.1), (3.2) and (3.6), where the aerodynamic forces and moments are functions of the instantaneous values of the orientation, the rotational velocity and the velocity of the center of gravity.

4. AERODYNAMICS

To solve the complete system of governing equations, it is necessary to know the values of the aerodynamic forces and moments at any given flight condition of the wing. For this purpose we use a strip-theory, where the wing is divided into a number of strips, on which the direction and magnitude of the aerodynamic forces are calculated independently of each other. By summing up the contributions of each strip, one gets the total amount of aerodynamic forces acting on the wing.

4.1 Calculation of local relative wind-velocity

The velocity of the center of gravity of the wing is given by the time derivative of the position vector:

$$\underline{u}_G = (\dot{x}_G, \dot{y}_G, \dot{z}_G) \qquad (4.1)$$

Denoting the position vector of a point P on the wing, given in body co-ordinates, as $\underline{r}^*_p$, the local relative wind-velocity $\underline{u}^*_p$, as the point P sees it, is given by the expression:

$$\underline{u}^*_p = [B](\underline{u}_{wind} - \underline{u}_G) - \underline{\omega}^* \times \underline{r}^*_p \qquad (4.2)$$

where the wind vector $\underline{u}_{wind}$ describes the wind field in inertial co-ordinates. $\underline{u}_{wind}$ is here given as the undisturbed scalar wind-velocity u_∞ in the y-direction:

$$\underline{u}_{wind} = (0, u_\infty, 0) \qquad (4.3)$$

4.2 Airfoil data

For the prediction of the aerodynamic forces acting on a
detached blade of a wind turbine, it is necessary to use air-
plane wing aerodynamics. Unfortunately there is only sparse
information in the literature concerning the problem of a wing
exposed to all combinations of the relative vector of wind-
velocity.

In Purser and Spearman [10] are shown the results of wind tun-
nel measurements of a yawed NACA 0012 wing having aspect ratio
$\Lambda = 6$. These measurements were made by yaw angles $\beta = 0^{\circ}$, 15°,
30°, 35°, 40°, 45°, 60° and 75° and angles of attack α run-
ning from 0° to either maximum lift or $\alpha = 55^{\circ}$, which was
the highest. The angle of attack α is defined as the angle
between the chord of the considered strip and the local rela-
tive wind-velocity, and the yaw angle β is defined as the
angle between the length axis of the wing and the local rela-
tive wind-velocity (see fig.2a and 2b). By combining these
measurements with more qualitative information from the avail-
able literature (e.g. Hoerner [4], Hoerner [5] and Critzos [2],
airfoil data for all possible combinations of α and β for
a NACA 0012 wing were constructed in Sørensen [12]. This idea
was based on Montgomerie [7] and Göransson [3].

5. TRAJECTORIES FOR DETACHED BLADES OF THE PROJECT K WIND-
TURBINE

In the following some typical trajectories for detachment of
the so-called Project K turbine, which is presently under deve-
lopment, will be shown and explained, and a study of the sensi-
tivity of the trajectories to changes in the conditions, by
which the blade is detached, will be carried out.

The Project K turbine is characterised by the following proper-
ties:

Tower height:	60 m
Blade radius:	30 m
Nominel tipvelocity:	70 m/s
Generator size:	1.5 - 2.0 MW
Weight of a blade:	ca. 8 tons

In Sørensen [12] it is shown that the maximum throw distance
for the K-turbine was obtained for detachment of the outer 1/3
of the blade. These calculations were carried out while the
rotor was running with 50% overspeed, corresponding to a tip-
velocity V_{TIP} = 100 m/s , and the blade was detached by an
azimuthal angle PHI = - 45° , where PHI is measured from
topposition positive in the rotational direction of the rotor.

5.1 Description of the trajectories

To get an impression of the time/spatial motion of a detached
wing, the trajectory for a 1/3-K-blade is visualised on fig.3a
and 3b. The detached wing is projected on the x-z-plane and the
x-y-plane (see fig.1), and it is plotted every 0.2 sec. The
rotational velocity of the rotor and by this the initial rota-
tion of the detached wing is 0.53 revolutions pr. sec.

As seen from the figures, the rotation of the wing in the
initial state of the throw is relatively unaffected by the
aerodynamic forces, but when the wing approaches its maximal
height, the influence of the aerodynamic forces on the rota-
tion becomes more dominant, and in the final stage of the
throw the initial rotation is "eaten up" by the aerodynamic
forces, and the wing falls down with its heavy end directed
downwards.

In previous investigations (Pedersen et.al. [8]) trajectories
were calculated by use of a ballistic model, where the drag
coefficient was kept constant and the lift forces were ignered.
The problem of using this model was the lack of knowledge of
the mean drag coefficient and the consequence of ignoring the
lift forces.

To get an impression of the magnitude of the mean drag coef-
ficient c_D and the influence of the lift forces, the calcu-
lated trajectory of the 1/3-K wing is compared to the ballistic
calculated trajectories on fig.4a and 4b.

These calculations were made with a wind-velocity u_∞ = 10 m/s,
and comparisons were made for mean drag coefficients $\bar{c}_D$ - 0.0,
0.1, 0.2, 0.3 and 0.4.

As seen by the trajectories, there is a relatively good agreement between the two models when projected on the x-z-plane, while the projection on the x-y-plane shows a bad agreement. This latter is due to the fact, that the deviation in the wind direction (y-direction) mainly is determined by lift forces, which means that the ballistic model is insufficient in describing this motion.

Characteristic of the deviation in the wind direction is, that it is determined in the initial stage of the throw. This indicates, that the thrust and by this the initial angles of attack are having a big influence on the prediction of the final throw distance. The mean drag coefficient was found to be approximately 0.25.

5.2 Sensitivity of trajectories and throw distances to changes in the conditions, by which the blade is detached

When calculating risk level zones, it is important to determine the parameters that significantly influence the prediction of the throw distances. Obviously tipvelocity and azimuth position of the blade plays the main role in the calculation of throw distances. But other parameters may be of importance. In the following the influence on the trajectories of the location of the center line of gravity, the pitch angle and the wind-velocity will be investigated.

5.2.1 Influence of the location of the center line of gravity

To investigate the influence of the location of the center line of gravity, trajectories were calculated for a 1/3-K-wing having different locations of the center line of gravity.

The outcome is shown on fig.5a and 5b. c_G denotes the position of the center line of gravity in percent of the chord length, measured from the leading edge.

As seen on the figures, the location of the center line of gravity are having a big influence on the trajectories and by this on the prediction of the throw distances. It is characteristic, that the closer the center line of gravity is located

to the leading edge, the longer throw distances will be the result.

The difference in the throw distances calculated with the center line of gravity located on the middle chord (c_G = 50%) and with the center line of gravity located on the quarter chord line (c_G = 25%) is found to be approximately 20%, while the difference in the throw distances between the locations c_G = 33% and c_G = 25% is negligible.

In general, the center line of gravity for blades of wind-turbines is located between c_G = 25% and c_G = 35% , hence a precise description of the location is not in general necessary.

5.2.2 Influence of the pitch angle

The pitch angle θ_p is defined as the angle between the tip of a blade and the plane of the rotor. θ_p is measured about the z^*-axis (see fig.1), and it is positive counterclockwise.

As shown in chap.5.1, the dependency of the trajectories on the thrust, at the time when the wing detaches, is relatively big. This means, that the influence of the pitch angle on the trajectories is also expected to be big.

On fig.6a and 6b trajectories for a 1/3-K wing, detached by different pitch angles, are shown. The largest throw distance is here obtained when θ_p = -10° , which is the pitch angle where maximum thrust is obtained. When θ_p reaches a positive value of a certain amount, the thrust changes sign, and the blade detaches in the opposite direction of the wind direction. This is seen on the figures for θ_p = 10° and θ_p = 20° .

In general, θ_p is seen to have a big influence on the prediction of throw distances.

5.2.3 Influence of the wind-velocity

On fig.7a and 7b trajectories for a 1/3-K wing, detached by different wind-velocities, are shown. As seen on the figures, the dependency of the throw distances on the wind-velocity is far from negligible. Increasing wind-velocity results in

increasing throw distances. This is due to the fact, that in-
creasing wind-velocity results in increasing thrust, at the
time when the wing detaches, and that the wind-velocity adds
an extra component to the relative velocity.

6. STATISTICAL MODELLING

In the following a statistical model, which gives the proba-
bility for a person being hit by a blade/blade-fragment, will
be described.

First we must determine under which circumstances a detach-
ment of a blade can take place. Here it is important to know
the wind-velocity, the wind direction, the azimuth position of
the blade, the pitch angle, the tip velocity and the position
of the break. This combination gives an infinite amount of
possibilities.

To treat such a problem in a numerical/statistical way, we must
a priori freeze some of the parameters and let the others as-
sume a set of values, which must be weighted by their respec-
tive values of probability.

For every value of the parameters a throw distance is calcu-
lated. The throw distance is given as the distance between
the wind turbine and the point of impact, where the point of
impact is defined as the point where the center of gravity of
the wing hits the ground.

After hitting the ground the wreckages of the wing covers an
impact area about the point of impact. The impact area is de-
fined as the area where a person will be hit by the wreckages.

Totally, the calculated impact areas define a risk zone in
which the probability for a person being hit by the wreckages
is finite.

The outer limit of the risk zone is given as the maximum throw
distance of the detached wing plus the movement of the wreck-
ages.

The risk zone is divided into ring areas with an equal division.

For each throw a ratio is made between that part of the impact area, which is covered be a certain ring, and the area of the ring.

For a specific throw one gets the local probability for hitting a person in a certain ring area, by multiplication of the ratio by the probability values of the variable parameters considered.

By summing up the local probability contributions for every throw, one gets the risk for a person being hit by the wreckages, as a function of that persons distance from the wind turbine, provided that the probability of detachment is unity.

6.1 Prediction of risk levels

As mentioned above, many parameters have an influence on the prediction of the risk level.

In the following, calculations will be made for a whole blade and the outer one third blade part of a Project K wind turbine.

As we do not know at which tip velocity a break may occur, calculations will be made for nominal tip velocity, appr. 50% overspeed, 100% overspeed, and appr. 200% overspeed, corresponding to 70 m/s, 100 m/s, 140 m/s and 200 m/s, respectively.

To limit the calculations we do not distinguish between different wind directions, and we specify a priori that the pitch angle does not differ from that of normal operation, when the blade breaks.

With these specifications, the calculations are made using the wind-velocity and the azimuthal position of the blade as the governing, variable parameters. Furthermore, we assume that the possible operating conditions of the wind turbine is given by the interval of wind-velocity: $u_\infty \in$ [7,5 m/s, 27,5 m/s], and that it is sufficient to describe the influence of the wind frequency distribution by considering 4 distinct wind-velocities, which all must be weighted by their relative probabilities. By use of Windatlas for Denmark (Petersen et.al. [9])

the relative probabilities α_k are determined as follows:

$$u_\infty = 10 \text{ m/s} \sim \alpha_{10} = 0.74$$

$$u_\infty = 15 \text{ m/s} \sim \alpha_{15} = 0.21$$

$$u_\infty = 20 \text{ m/s} \sim \alpha_{20} = 0.03$$

$$u_\infty = 25 \text{ m/s} \sim \alpha_{25} = 0.02$$

where each wind-velocity represents the interval:

$$u_\infty \in [- 2.5 + u_\infty, u_\infty + 2.5]$$

As the rotor turns, its azimuthal angle changes cyclically, and we assume that equal probability will be obtained for a break at all azimuthal angles. Now, we divide the plane of the rotor into 16 sectors, where a single throw in a given sector represents all possible throws at that specific sector. The probability for detachment in a certain sector is then 1/16. By 4 different wind-velocities and 16 azimuthal positions, the probability distribution for a given detached blade/blade-fragment, having a certain tip velocity, is represented by 64 throws.

In Sørensen [13] it was shown that the impact area A_N, which was approximated by a rectangel, could be expressed by the following expression :

$$A_N = \frac{\pi}{2}(1.0 + L_{max})^2/\sin v + 2(1.0 + L_{max})\ell + \frac{\pi}{2}(1.0 + L_{max})^2 \quad (6.1)$$

And the lenght of the impact area L_N could be expressed by :

$$L_N = \ell + \frac{\pi}{4}(1.0 + L_{max})/\sin v + \frac{\pi}{4}(1.0 + L_{max}) \quad (6.2)$$

Where L_{max} is the distance from the center of gravity to the farthest edge of the wing, v is the angle of impact and ℓ is the displacement of the wreckages.

The displacement of the wreckages was estimated as follows :

$$\ell = \begin{cases} R/3 & \text{for} \quad R < 75 \text{ m} \\ 25 \text{ m} & \text{for} \quad R \geq 75 \text{ m} \end{cases} \quad (6.3)$$

R denotes the throw distance.

The expressions (6.1) and (6.2) was derived by assuming, that the fall of the wing was connected by violent rotations, when hitting the ground. As the actual rotation is limited, the assumption is on the safe side.

On fig.8 the outer limit of the risk zones, as function of the tip velocity, is shown for the whole blade and the one third outer blade part of a Project K turbine. By interpolation between the two curves, the outer limit can be estimated for detachment of any blade fragment of the Project K turbine.

As seen on the figure, the maximum throw distance depend highly on the tip velocity. If a whole blade detaches at v_{TIP} = 70 m/s, the outer limit of the risk zone is 120 m, and if it detaches at v_{TIP} = 200 m/s, the outer limit is 325 m. For detachment of the one third outer blade part, the outer limit of the risk zone is 360 m for v_{TIP} = 70 m/s, and 780 m for v_{TIP} = 200 m/s.

The probability distribution for detachment of the one third blade fragment, as function of distance from the wind turbine, is plotted for different tip velocities on fig.9. Similar curves for detachment of a whole blade are shown on fig.10. Close to the tower of the wind turbine the probability is relatively high, and, as seen on the figures, the probabilities exhibit both a local minimum and a local maximum.

To calculate the annual frequency of human damage, the results shown on fig.9 and fig.10 must be multiplied by the annual frequency of the considered event.

An evaluation of possible events of failures and a determination of the corresponding annual frequencies demands either an analysis of the components of the wind turbine or an analysis of experiences from actual failures. Such an evaluation was outside the scope of the present work.

REFERENCES

[1]   Bramwell, A.R.S.   (1976)   Helicopter Dynamics.
          Edward Arnold, London.

[2]   Critzos, C.C., Heyson, H.H. & Boswinkle, R.W.   (1955)
          Aerodynamic Characteristics of NACA 0012 Airfoil
          Section at Angles at Attack from 0° to 180°.
          NACA Technical Note 3361, Washington.

[3]   Göransson, P.   (1982)   A litterature investigation and
          computation of steady aerodynamic forces and moment
          resulting from all combinations of angles of attack
          and yaw angles applied to a plane wing.
          FFA HU-2334:1, Stockholm.

[4]   Hoerner, S.F.   (1965)   Fluid-Dynamic Drag.
          Published by the Author.

[5]   Hoerner, S.F. & Bort, H.V.   (1975)   Fluid-Dynamic Lift.
          Published by Mrs. Liselotte A. Hoerner.

[6]   Kreyszig, E.   (1968)   "Advanced Engineering Methematics"
          Wiley International Edition, USA.

[7]   Montgomerie, B.   (1982)   Horisontal axis wind turbine
          blade failure, blade fragment six degrees of free-
          dom trajectory, site risk level prediction.
          Wind Energy Systems, Vol.2, pp.389-401,
          BHRA, Cranfield.

[8]   Pedersen, B.M. & Bugge, J.A.C.   (1980)   On safety
          distances for wind turbines (in Danish).
          AFM Notat VK-63-800527, Lyngby.

[9]   Petersen, E.L. et.al.   (1981)   Windatlas for Denmark,
          Risø-R-428, Roskilde.

[10]   Purser, P.E. & Spearman, M.L.   (1951)   Wind-tunnel
          tests at low speed of swept and yawed wings having
          various plan forms.
          NACA Technical Note 2445, Washington.

[11]   Sørensen, J.N.   (1982)   Calculation of the trajectory
          through the air of a blade detached from a wind
          turbine (in Danish).
          AFM 82-06, Lyngby.

[12]   Sørensen, J.N.   (1983)   Flight path and throw distance
          of a blade detached from a wind turbine (in Danish)
          AFM 83-06, Lyngby.

[13]   Sørensen, J.N.   (1983)   Determination of the risk for
          human damage by detachment of a blade from a wind
          turbine (in Danish).
          AFM 83-07, Lyngby.

[14]   Wortmann, F.X.   (1978)   Wie weit kann das Blatt einer
          Windturbine fliegen?
          Kurtzvortrag ET 4086A/ET 4088, Universität Stuttgart,
          Institut für Aerodynamik und Gasdynamik.
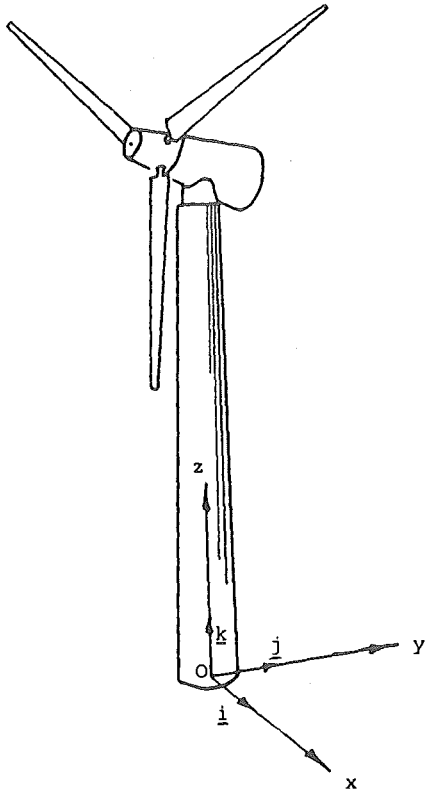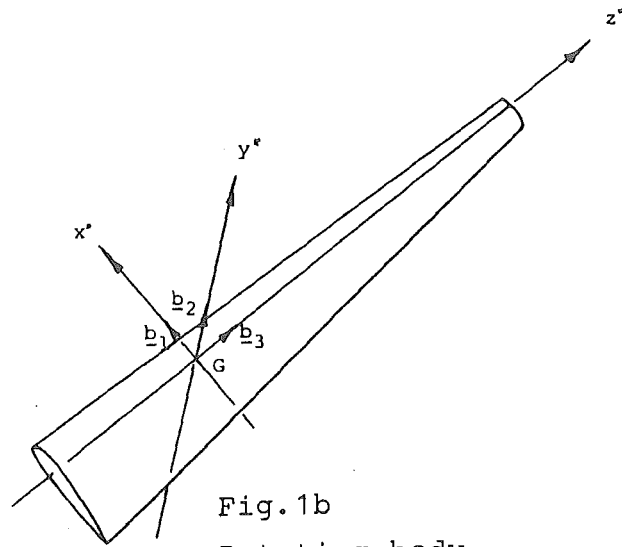
Fig.1b
Rotating body
co-ordinate system

Fig.1a
Global inertial
co-ordinate system
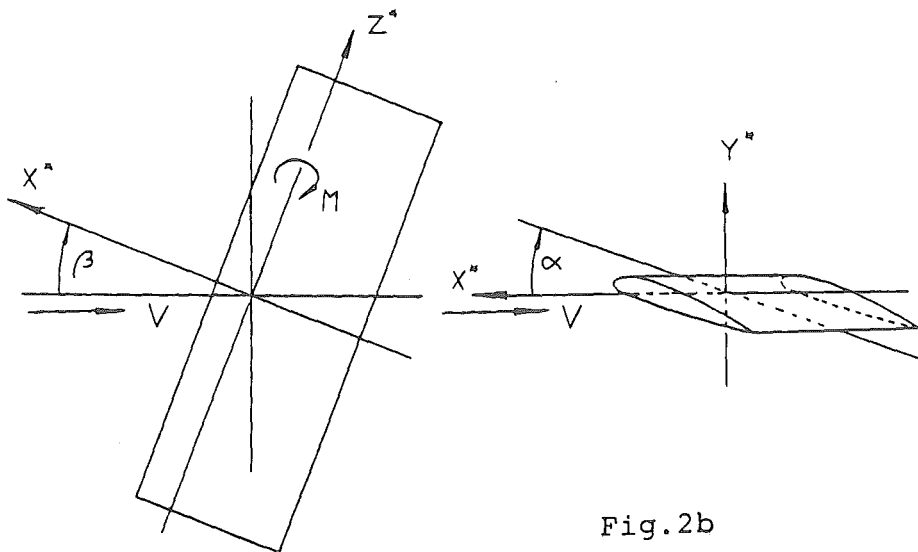
Fig.2a
Definition of angle
of attack α

Fig.2b
Definition of
yaw angle β
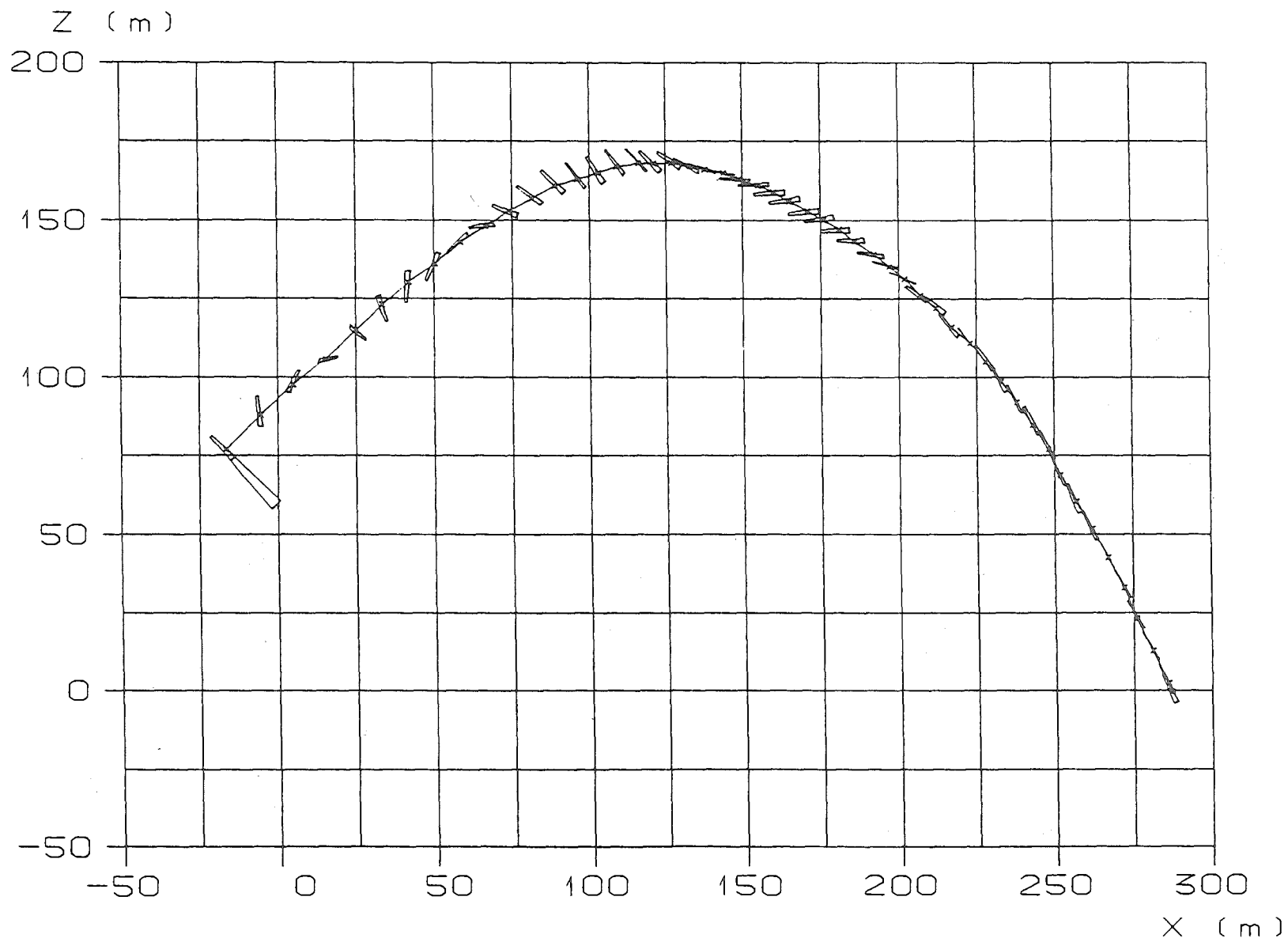
Fig.3a

Time/spatial motion of a 1/3 K blade
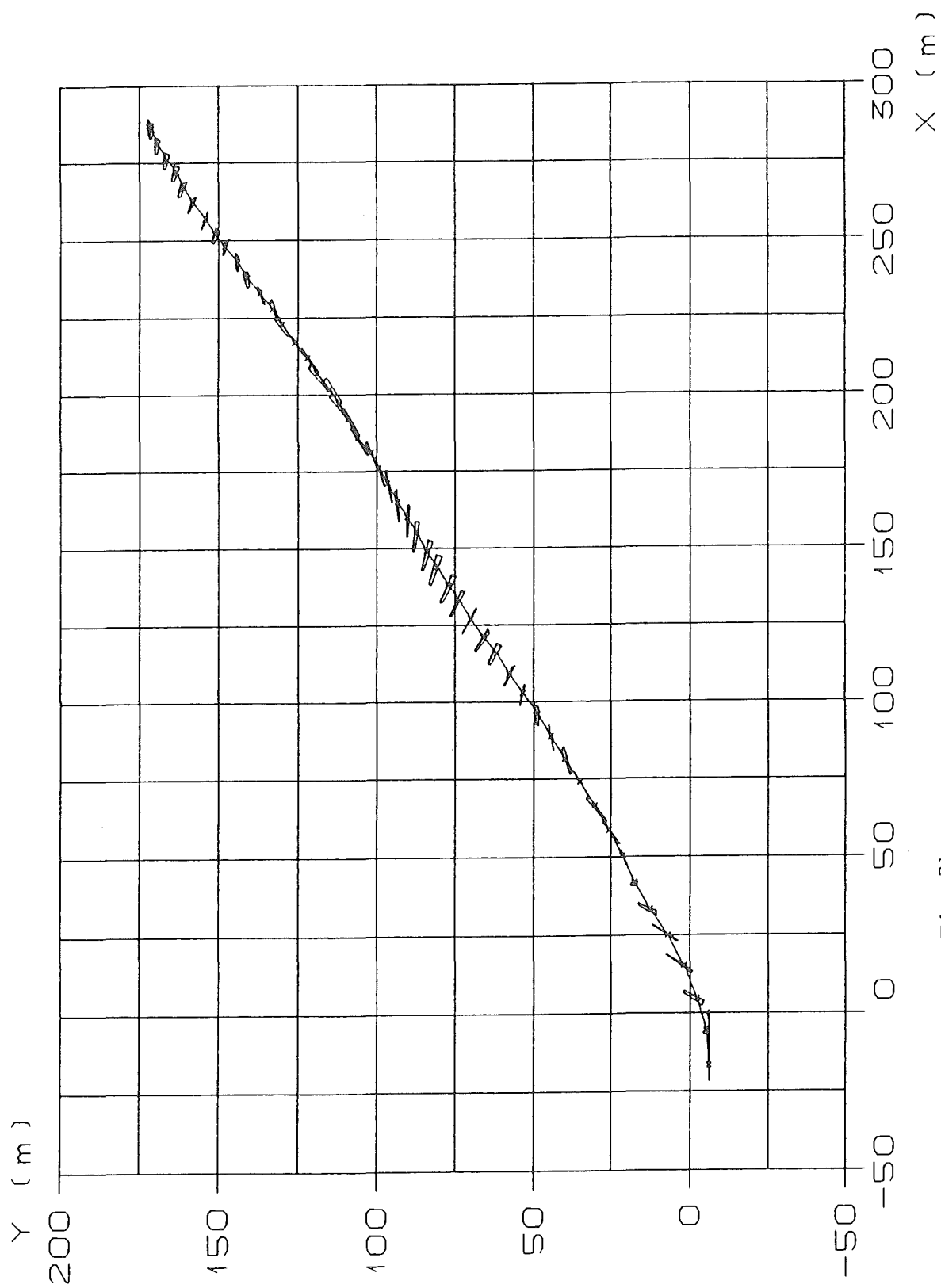
Fig.3b
Time/spatial motion of a 1/3 K blade
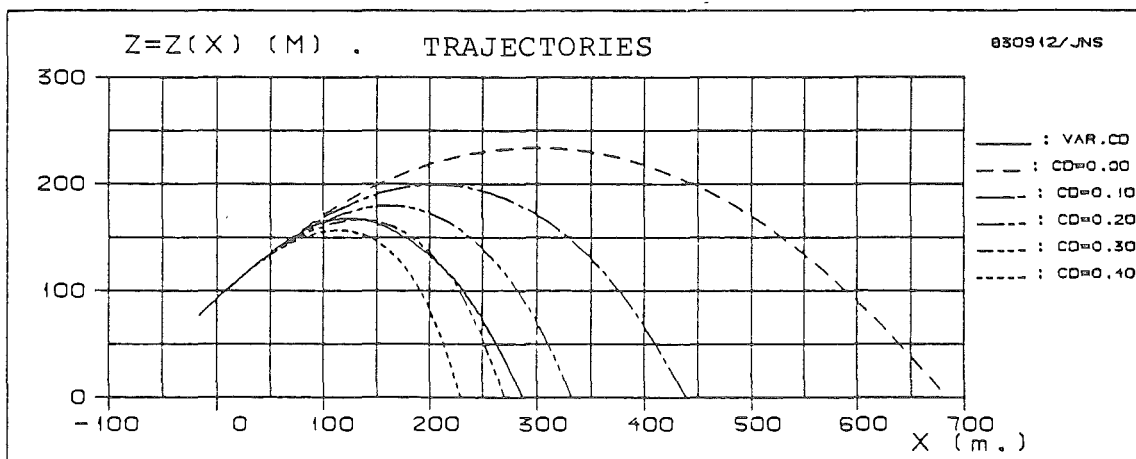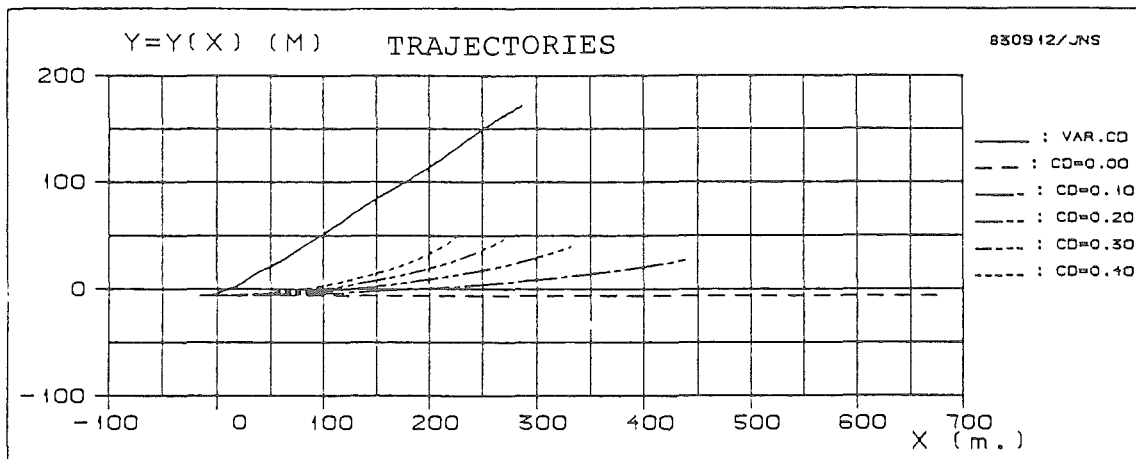
Fig.4a and 4b
Comparison of trajectory, calculated by present method, by
ballistic calculated trajectories for a detached 1/3 K blade
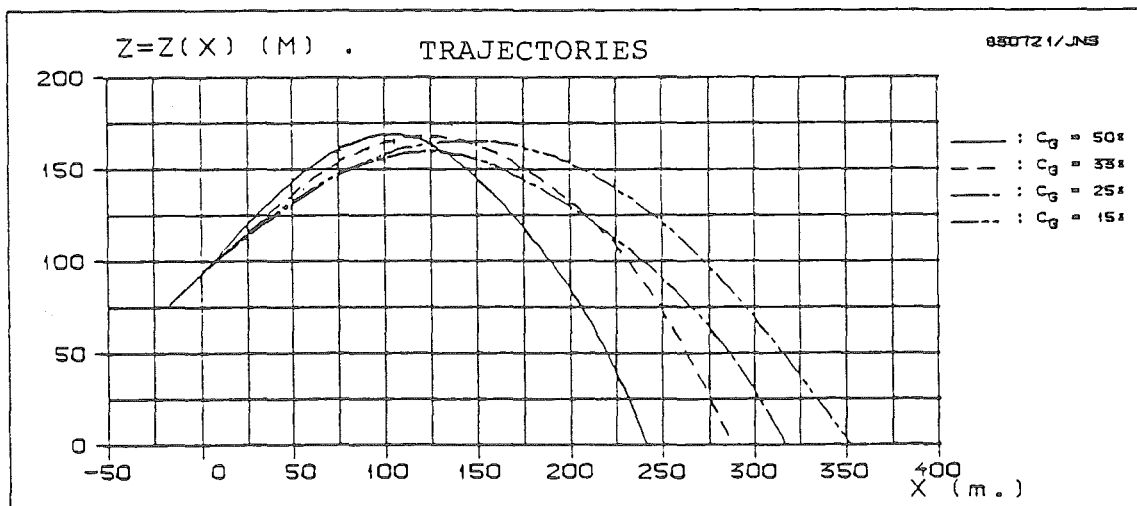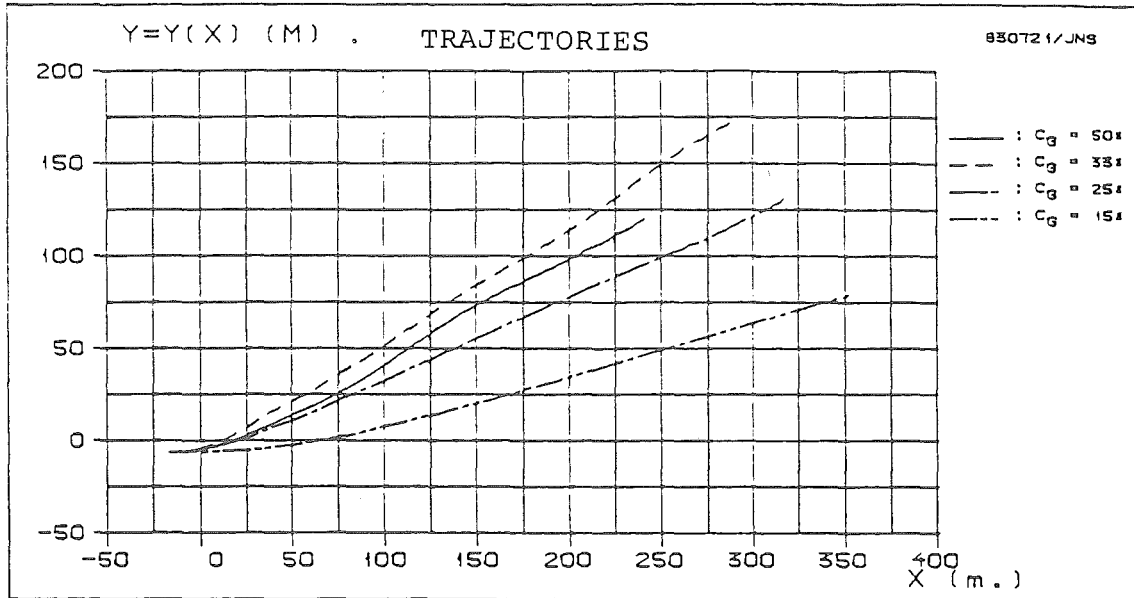
Fig.5a and 5b
Influence of the location of the center line of gravity
on the trajectories of a detached 1/3 K blade
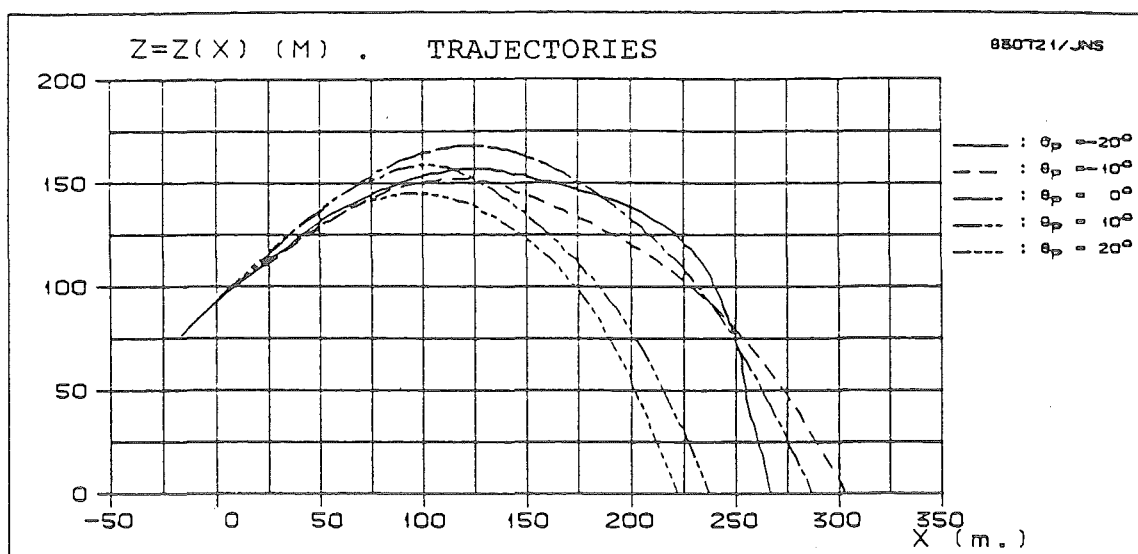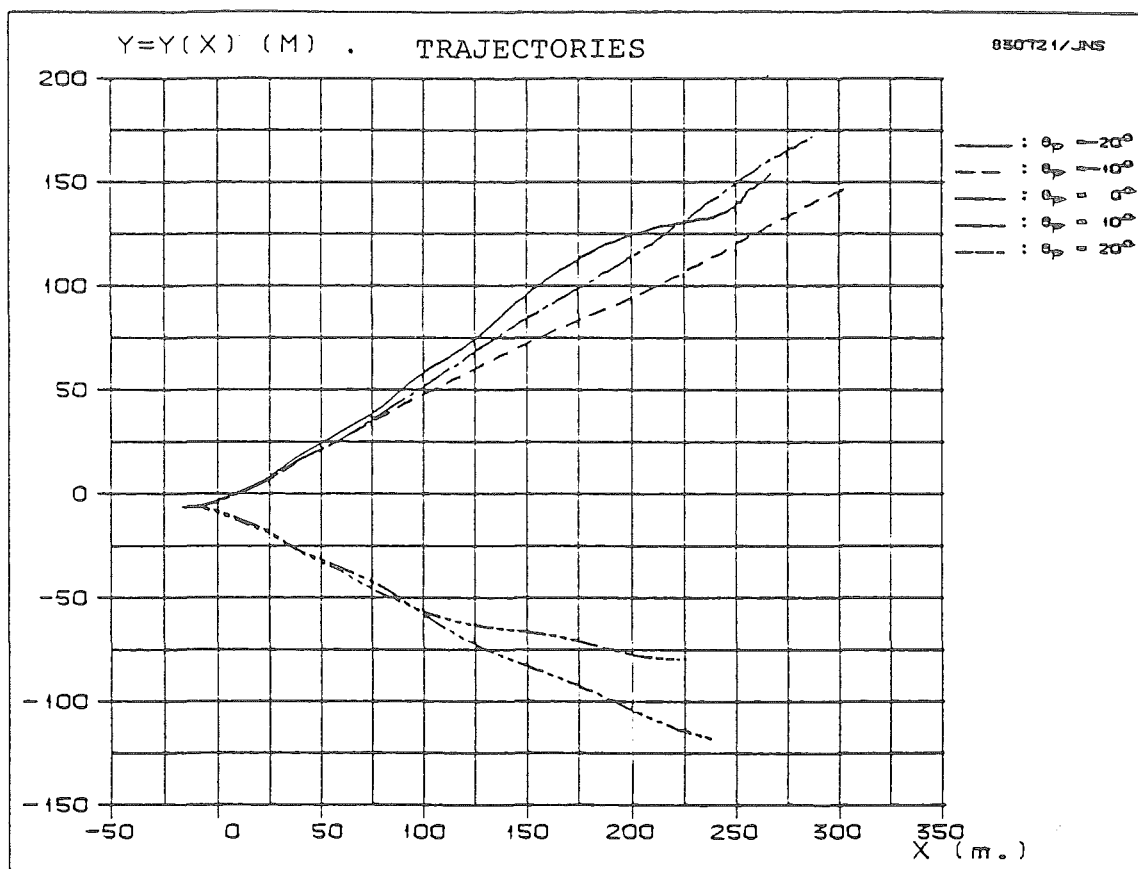
Fig.6a and 6b

Influence of the pitch angle on the trajectories

of a detached 1/3 K blade
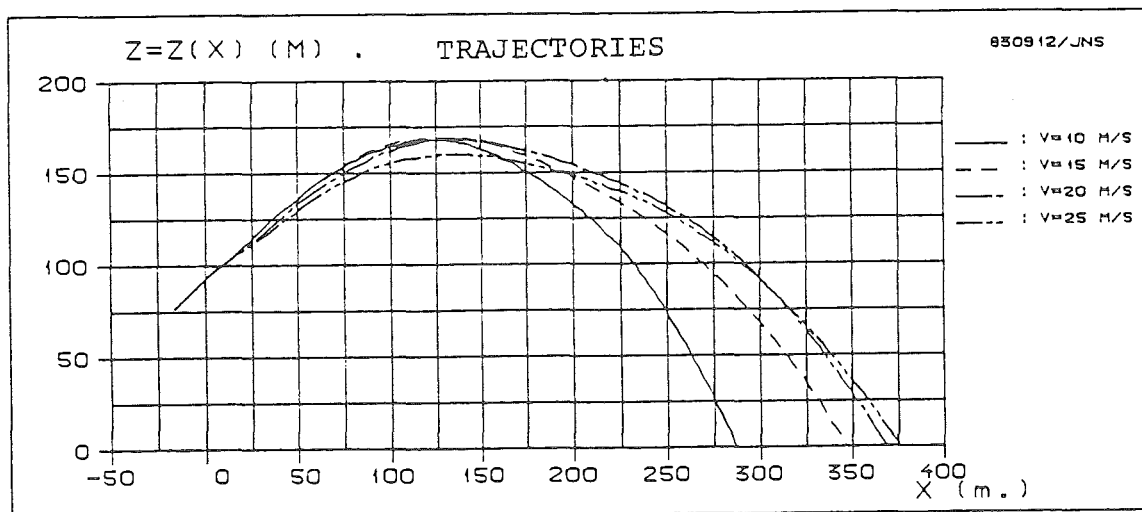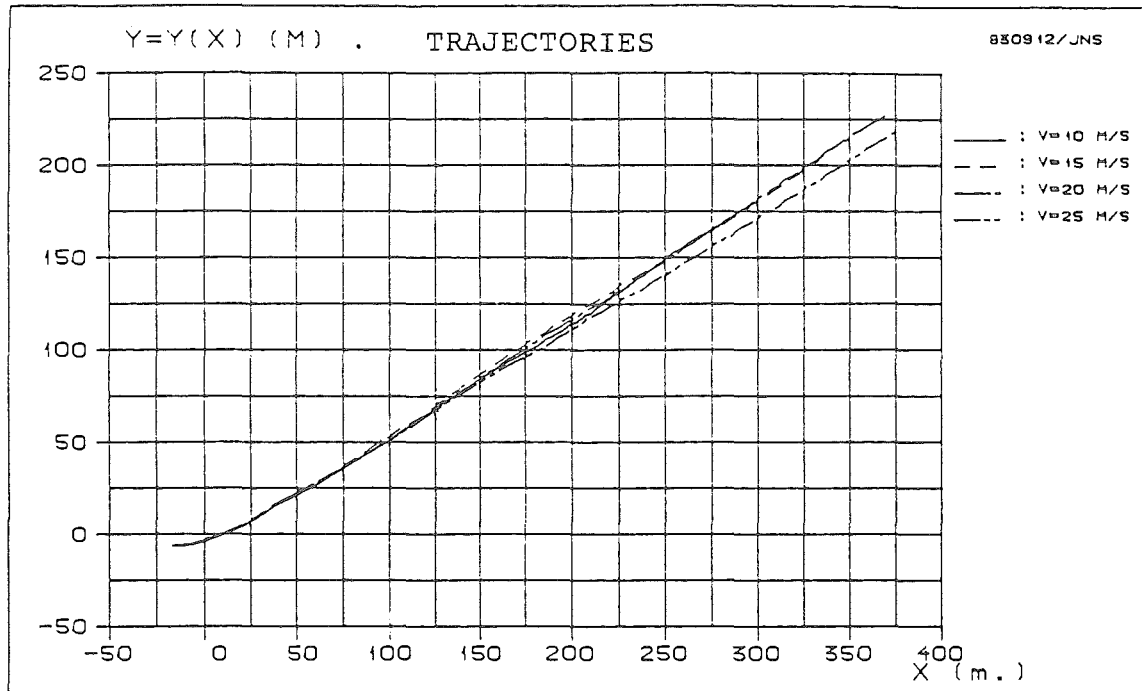
Fig.7a and 7b
Influence of the wind velocity on the trajectories
of a detached 1/3 K blade
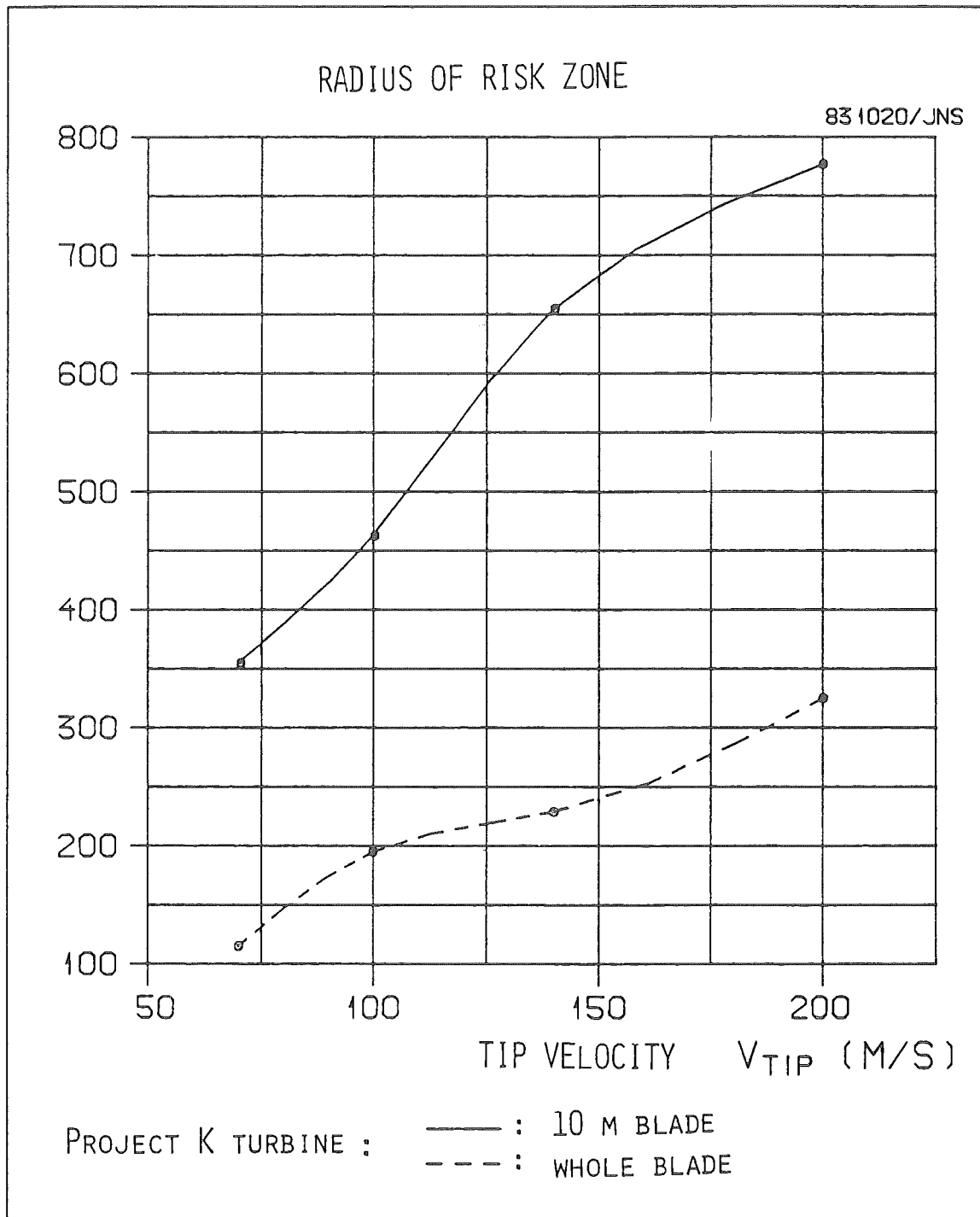
Fig.8
Outer limit of the risk zones as function of tip velocity
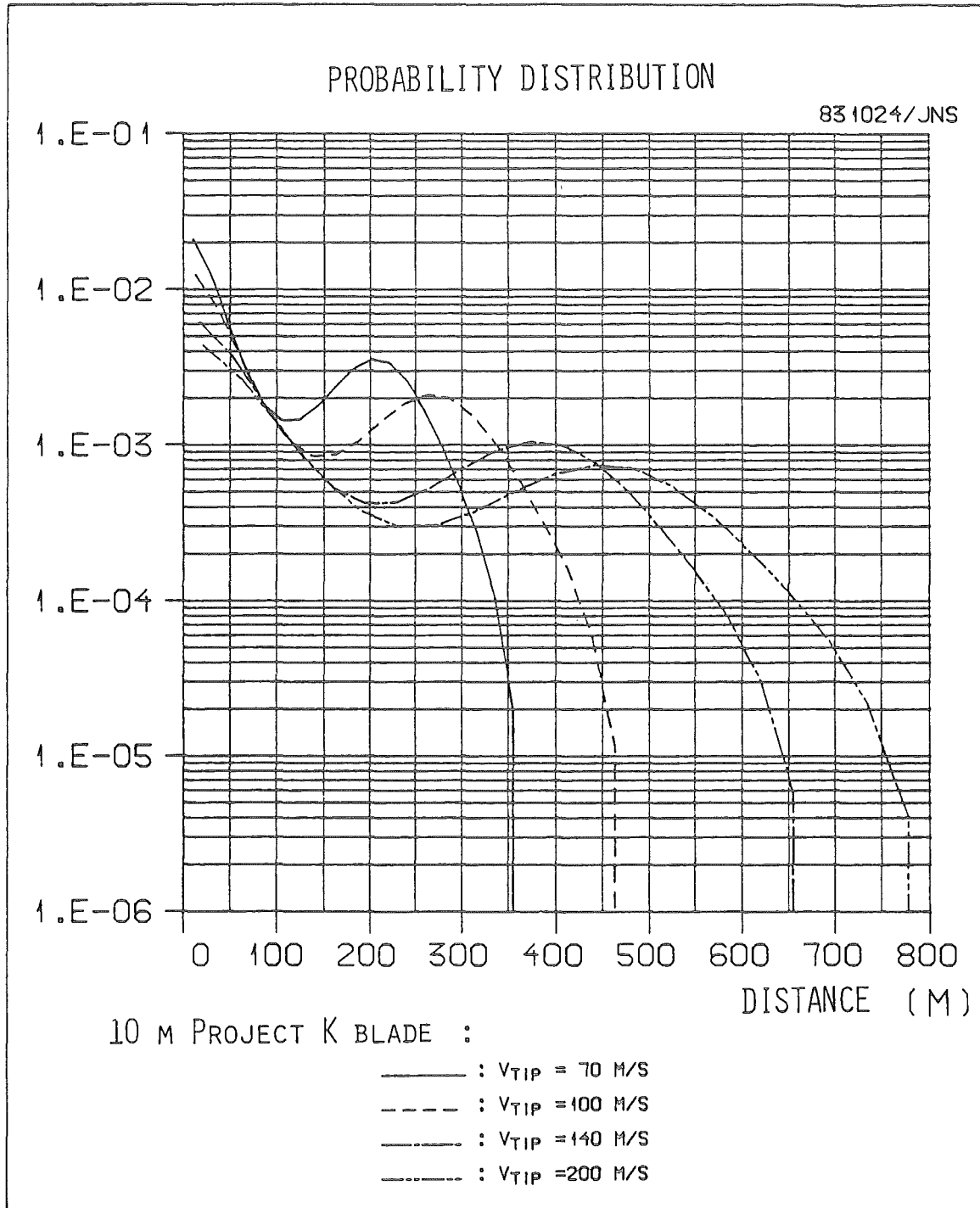
Fig.9
Probability distributions for a 1/3 K blade
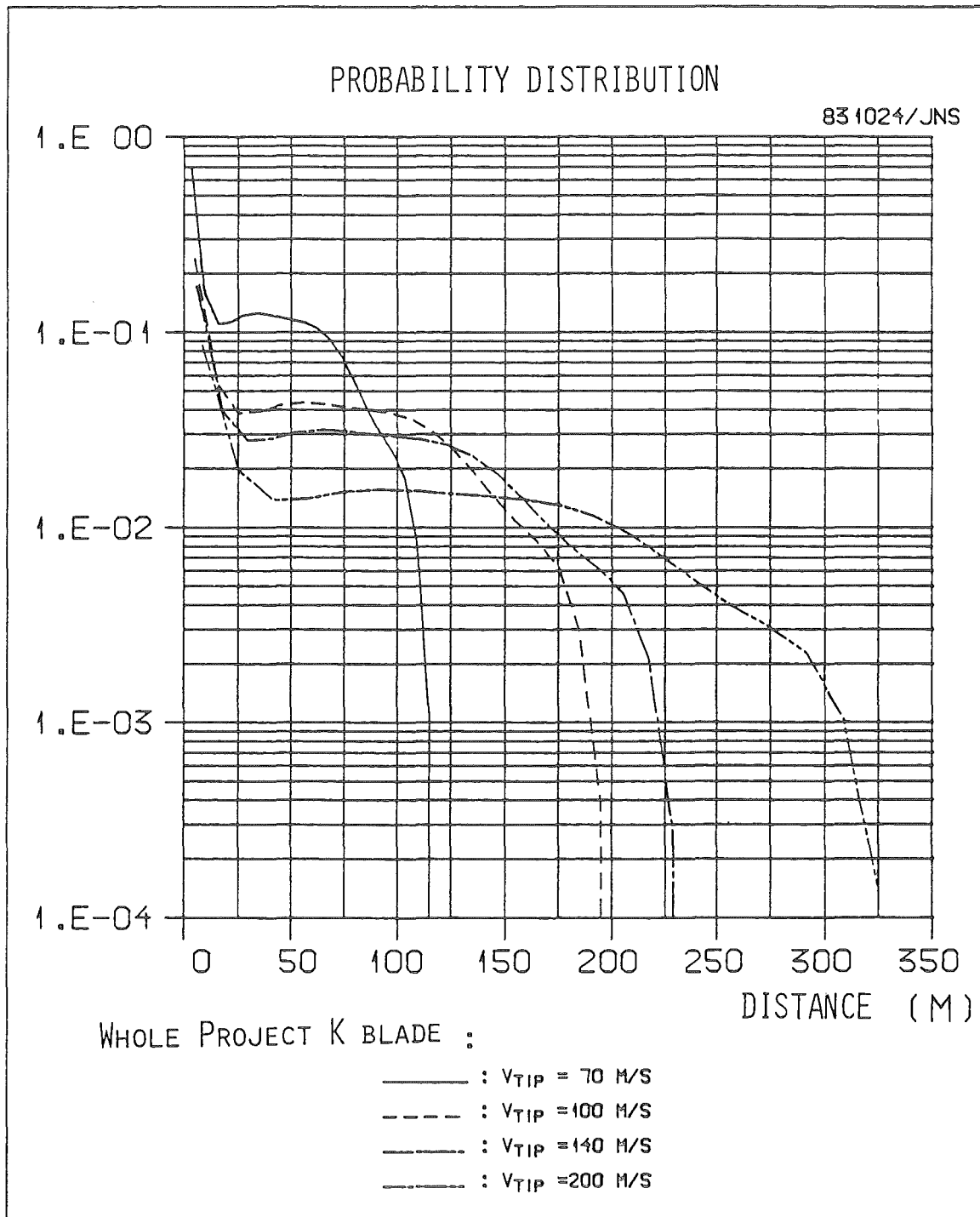
Fig.10

Probability distributions for a whole Project K blade

GROWIAN

First Observations of the

Environmental Impact at the GROWIAN Site

Friedrich Körber

Environmental impact at the GROWIAN site

At the GROWIAN site first investigations on environmental impact
by sound emission and TV interference were conducted. A short
glance on the wind generator's operation statistics shows that
only general observations were possible till now, because of
little operation time in real energy production conditions.

OPERATION STATISTICS   30.04.1984

Overall operation time (rotational)   70 h
at rated speed   60 h
connected to grid   14 h
Energy production   18000 kWh

1. Sound emission

In first observations of the subjective sound impression to the
human ear it was found that the noise from the rotor in idle
operation could be recognized 2000 m in the downwind direction
and about 1000 m upwind. Infranoise was not observed. See
figure 1.

In partial power operation GROWIAN emits a noise frequency spec-
trum from 30 to 2000 Hz with a distinct peak at 200 Hz. This is
produced by the second stage of the three stage planetary gear
box. Full power noise tests were not conducted till now. Projections
however predict about 56 dBA at 3 MW power in a distance of 250 m
on the ground.

Data of structural noise in the steel nacelle provides figure 2.

2. TV Interference

In the field of electromagnetic interference first tests were conducted by visual observation of a mobile TV set in the surrounding of the WEC. The results were:

- 2 x vertical jump of picture per rotor rotation.

- Interference at vertical or horizontal rotorblade position (depending on polarisation of the transmitter)

- Only shading effects, no reflection

- No interference on TV sound

- No ghosts or double images on TV screen

Figure 3 shows the areas with reception interference in the neighbourhood of GROWIAN.

For the future intensive measurements of the field strength of the radio waves are planned.
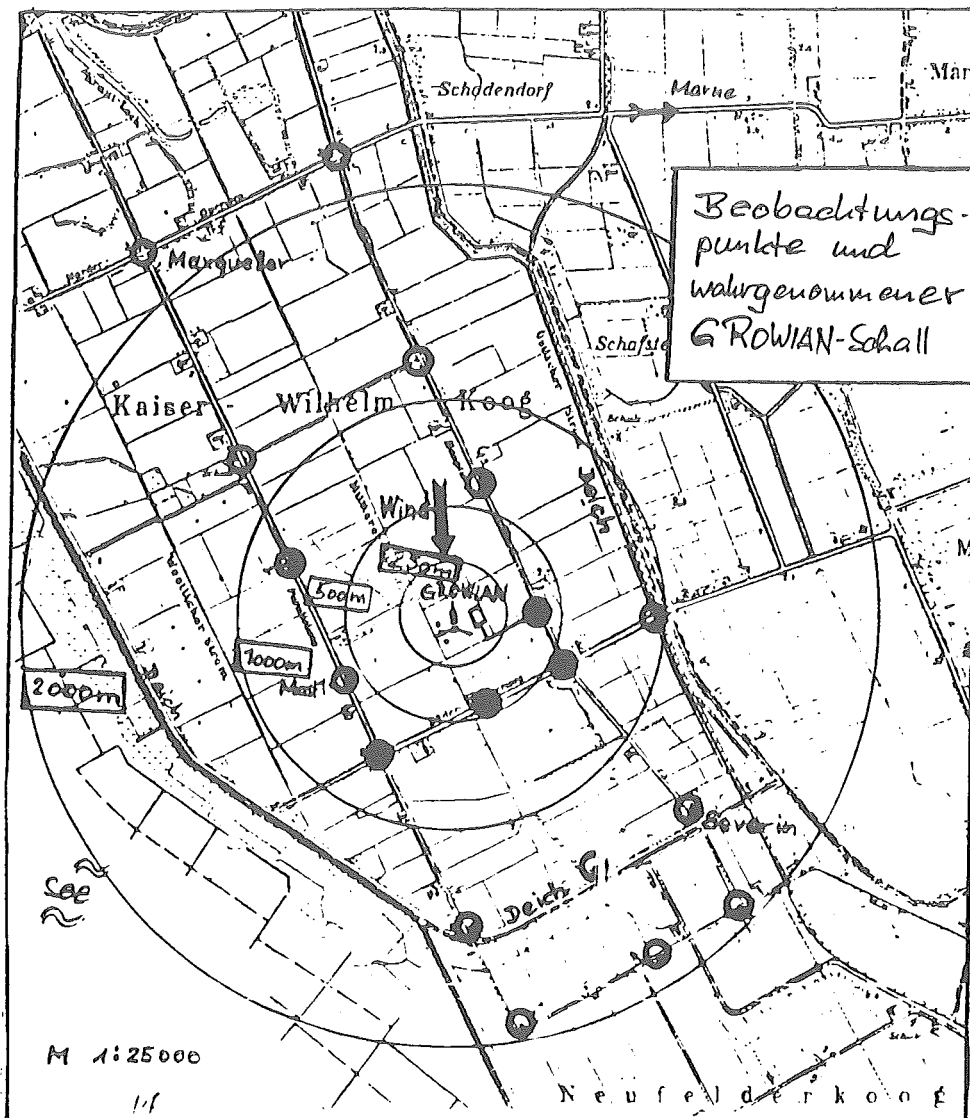
Fig. 1
Aerodynamic noise.
Intensity in different distances

Beobachtungs-
punkte und
wahrgenommener
GROWIAN-Schall

○ No noise
◔ Very low
◑ Low rushing
◐ Swelling rushing
● Distinct sw. rushing
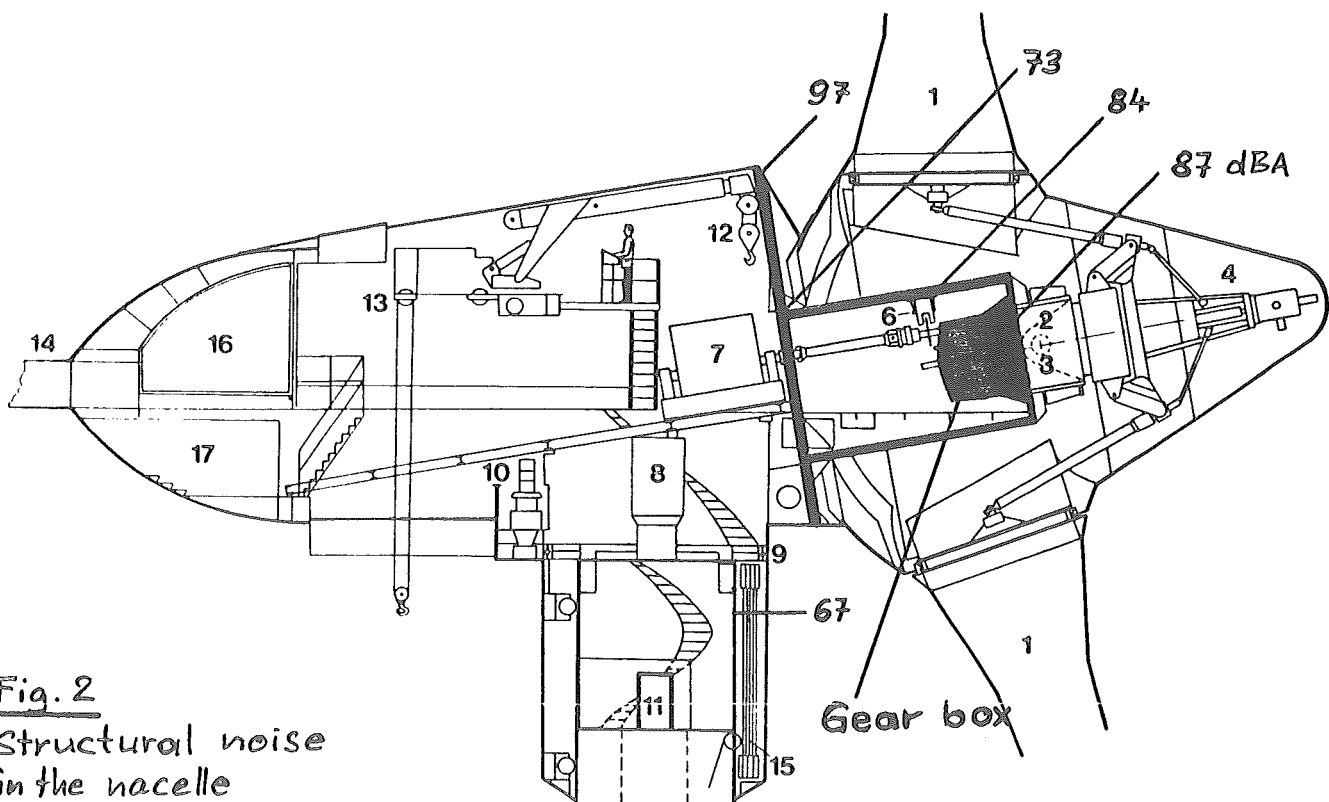
M 1:25000

Fig. 2
Structural noise
in the nacelle

97   73
     1   84
          87 dBA

TV Supply
Fernsehversorgung
im Kaiser-Wilhelm-
koog
(Standort GROWIAN)

Heide
UHF

Sea

VHF

Cuxhaven

GROWIAN

UHF

Hamburg

Sender Heide
Transmitter Heide

k o o g

Marnerdeic

k o o g

Schafstedt

Fah

1000 m

500 m

250 m

Marner·

Gestörter Empfang von
Sender Cuxhaven
Interference of
transmitter Cuxhaven

Neue

Gestörter Empf
von S. Heide
Interference of
transmitter Heide

Sender
Cuxhaven
Transmitter C.

Kaiser - Wilhelm
Koog

Sender
Hamburg

M 1:25000

N e u f e l d e r k o o g

Fig. 3   TV interference

WIND TURBINE NOISE
Prediction Tools and Design Parameter Dependence

by

Staffan Meijer

ABSTRACT

A short description of some possible aerodynamic noise sources is presented.

The influence of turbine design parameters (diameter, r.p.m., power etc.) on noise levels predicted by theoretical models is discussed. One example is the possibility of running a turbine with variable r.p.m., which will have great influence on low as well as on high frequency noise emission.

Measurements of noise emission from the WECS at Maglarp Sweden will be presented and compared to theoretical predictions.

Estimates of how the noise from this turbine can be lowered by design parameter changes are presented.

The Maglarp Wind Turbine

Number of Blades	2
Rotor Diameter	78 m
Tower Height	80 m
Rotational Speed	25 rpm
Rated Power	3 MW
Cut-in Wind Speed	5-7 m/s
Cut-out Wind Speed	21 m/s
Rated Wind Speed	14 m/s

NOISE SOURCES

Low Frequency Noise Sources

Steady Blade Loading (Gutin Noise)

Incident Turbulence-Unsteady Loading Noise

Blade Tower Passage Noise

High Frequency Noise Sources

Turbulent Boundary Layer Trailing Edge Noise   TBL-TE

Turbulent Wake Noise

Separated Flow Noise

Laminar Boundary Layer Self Noise

Noise Measurements

1/3 Octave Band Spectrum (Lin.)

Measurement point 120 m downwind

Wind velocity 7–8 m/s

THE MAGLARP WIND TURBINE

dB REL.

FREKVENS Hz
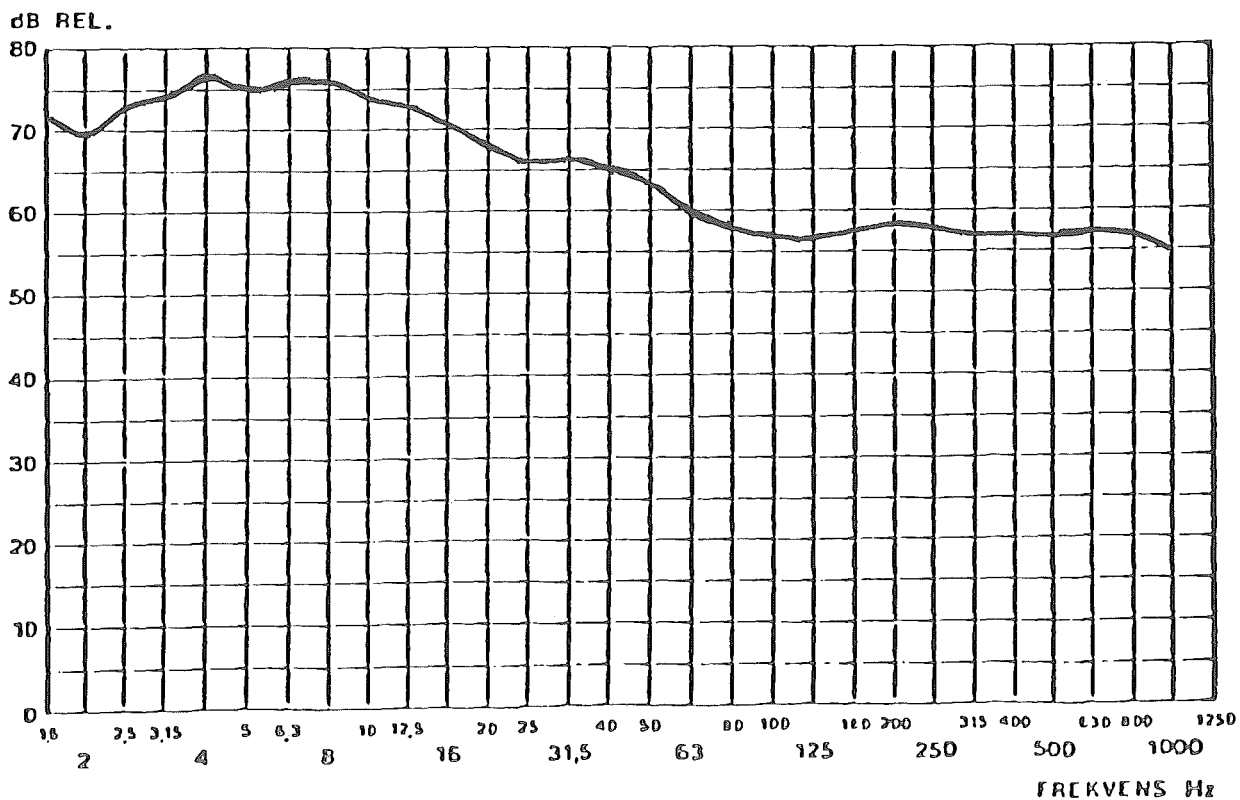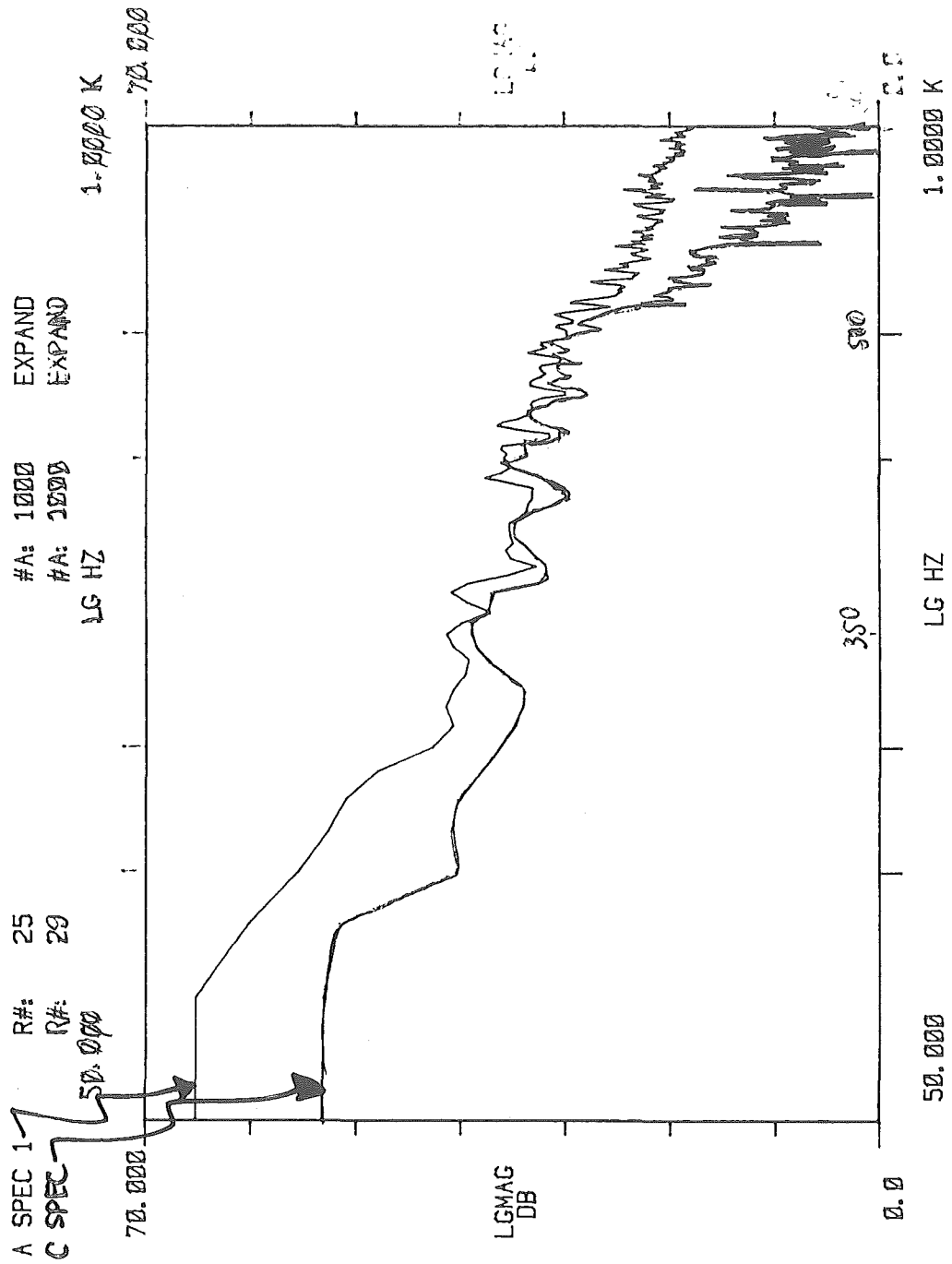
Octave Band Spectrum

Measurement point 200 m downwind

THE MAGLARP WIND TURBINE

Octave band spectrum chart with curves labeled 15–20 m/s, 10–15 m/s, 5–10 m/s; dB axis versus Hz.
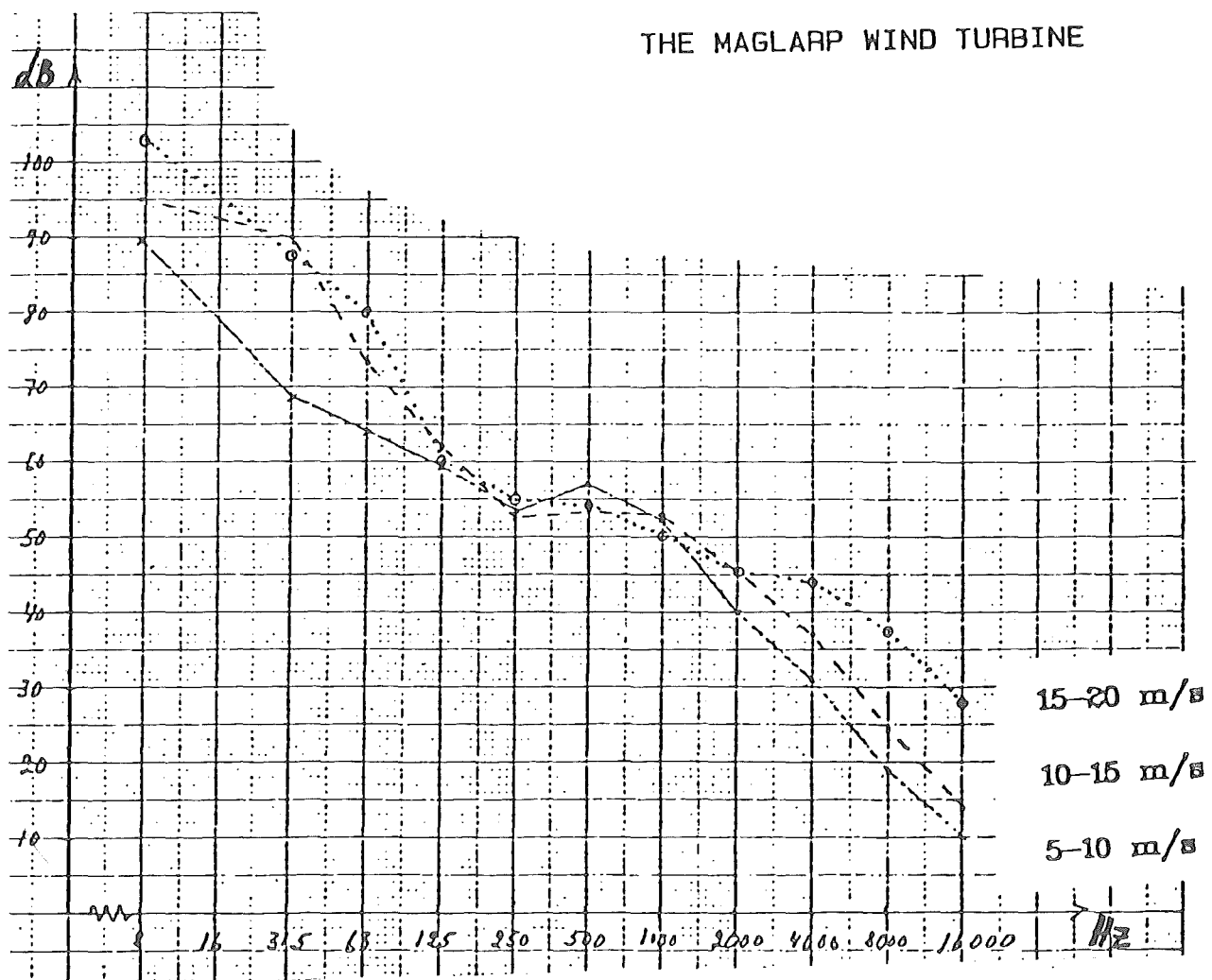
Background Noise Octave Band Spectrum

THE MAGLARP WIND TURBINE

15–20 m/s

10–15 m/s

5–10 m/s
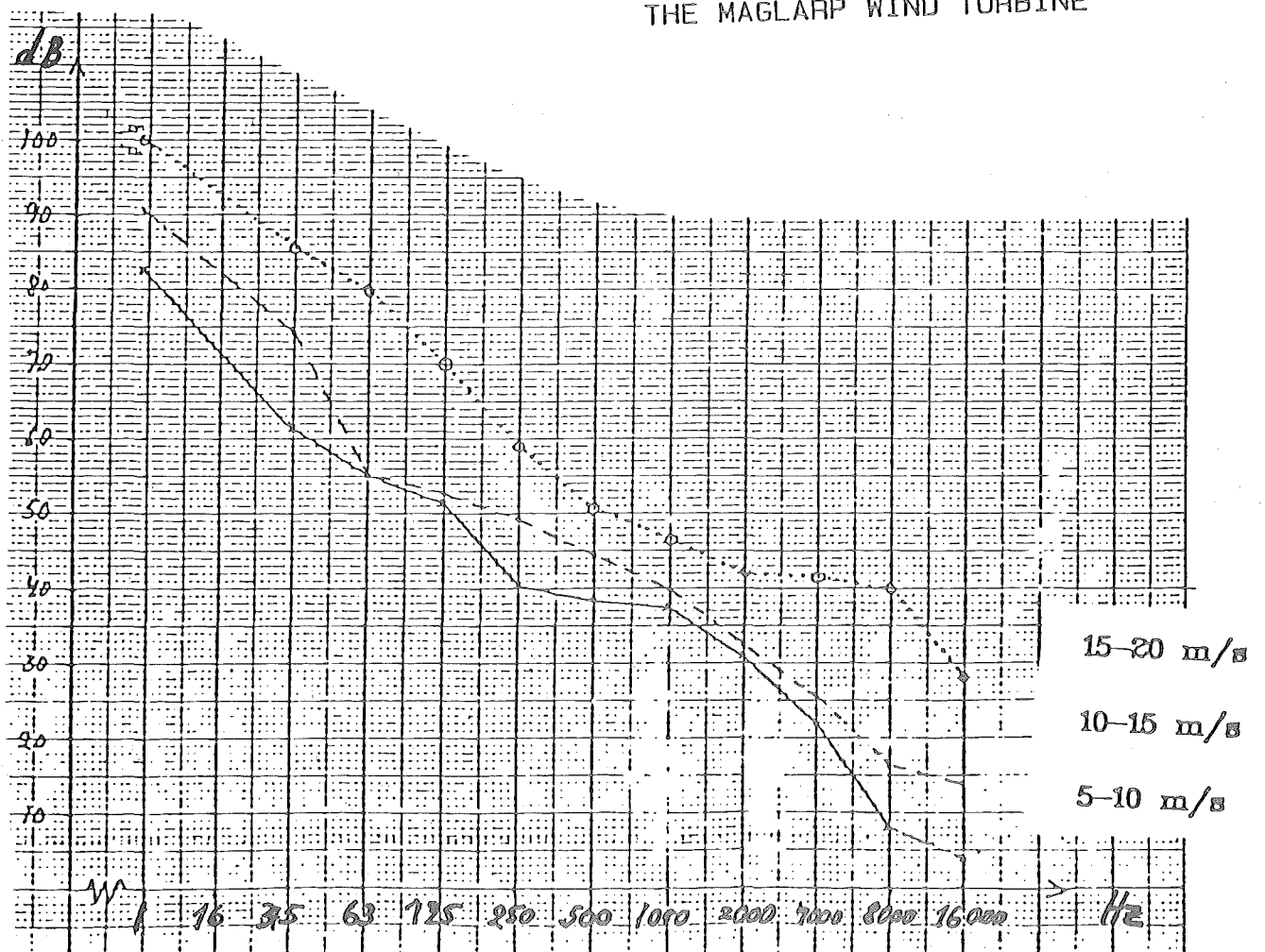
Pressure Signal

Measurement point 120 m downwind

Wind velocity 7-8 m/s

TI AVG 1   RW₁   65
TI AVG 2   RW₁   66   THE MAGLARP WIND TURBINE
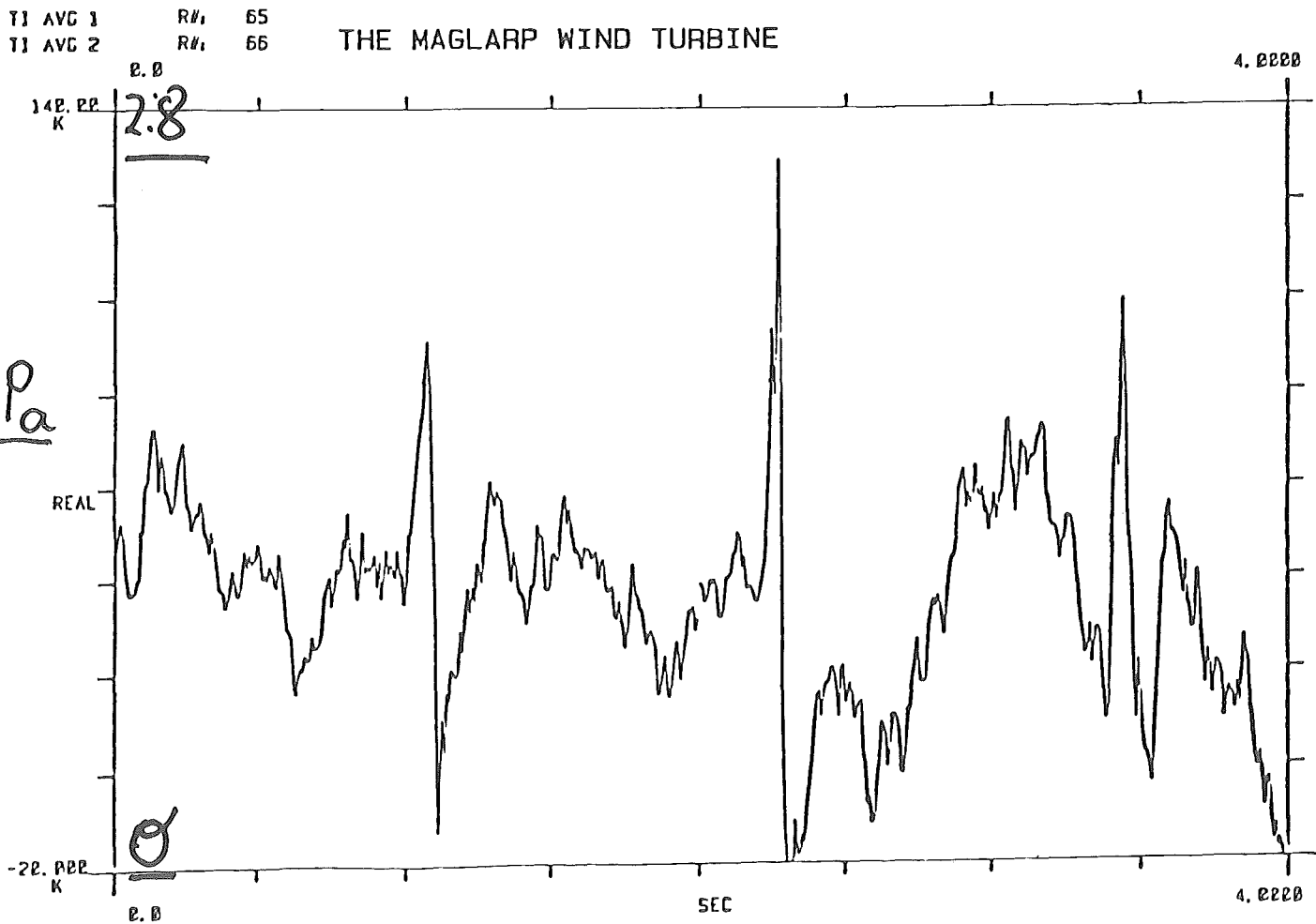
Steady Blade Loading (Gutin Noise)

Computation of Gutin Noise

Simplifications

Blade forces projected to rotor plane

Blade thickness neglected

$D \ll R$

      D   Rotor diameter

      R   Distance to observer

GUTIN NOISE FOR THE MAGLARP WIND TURBINE

Time signal at angle theta= 80.0 degrees where
the maximum sound pressure level is 69.4 dB

RPM = 25.0
Wind speed = 8.0 m/s
Distance = 0.1 km

Time (Period=0.120E+01 sec)
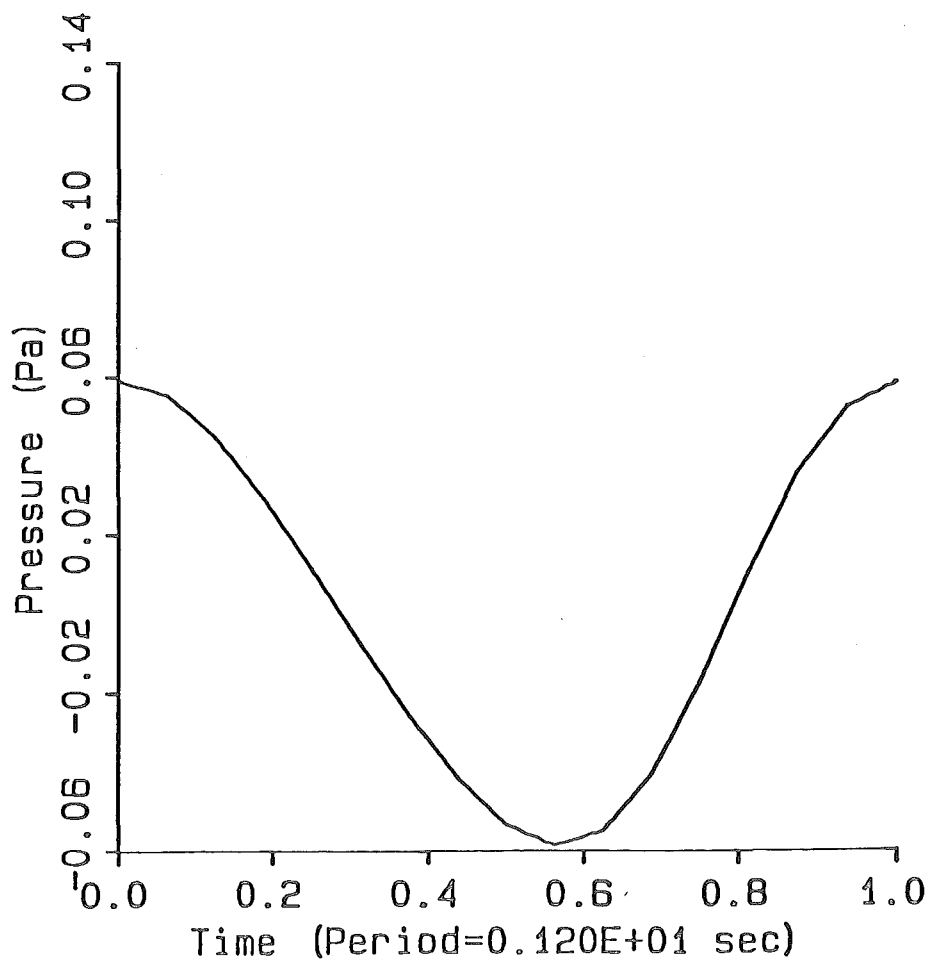
GUTIN NOISE FOR THE MAGLARP WIND TURBINE

Sound pressure level at angle theta= 80.0 degrees
for the Fourier components of the time signal

RPM = 25.0
Wind speed = 9.0 m/
Distance = 0.1 km
OASPL=0.663E+02 dB

Harmonic number (BPF=0.833E+00 Hz)
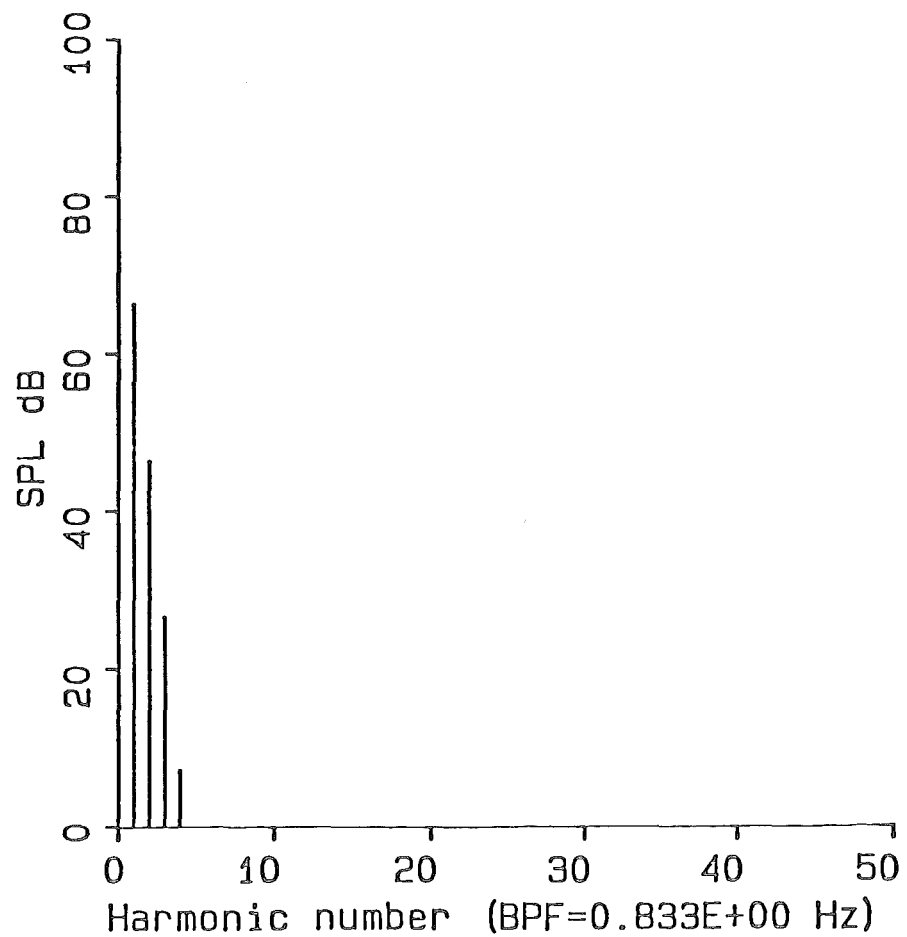
Incident Turbulence–Unsteady Loading Noise

Computation of Incident Turbulence Noise

Model of atmospheric turbulence

Linearized aerofoil response to a two–dimensional gust

Loading on different blade segments uncorrelated

Sound pressure level in 1/3 octave band

RPM = 25.0
Windspeed =   7.5 m/s
Distance to observer =   0.14 km
OASPL=0.635E+02 dB   OASPL*=0.701E+02 dB
                                    f*= 278. Hz
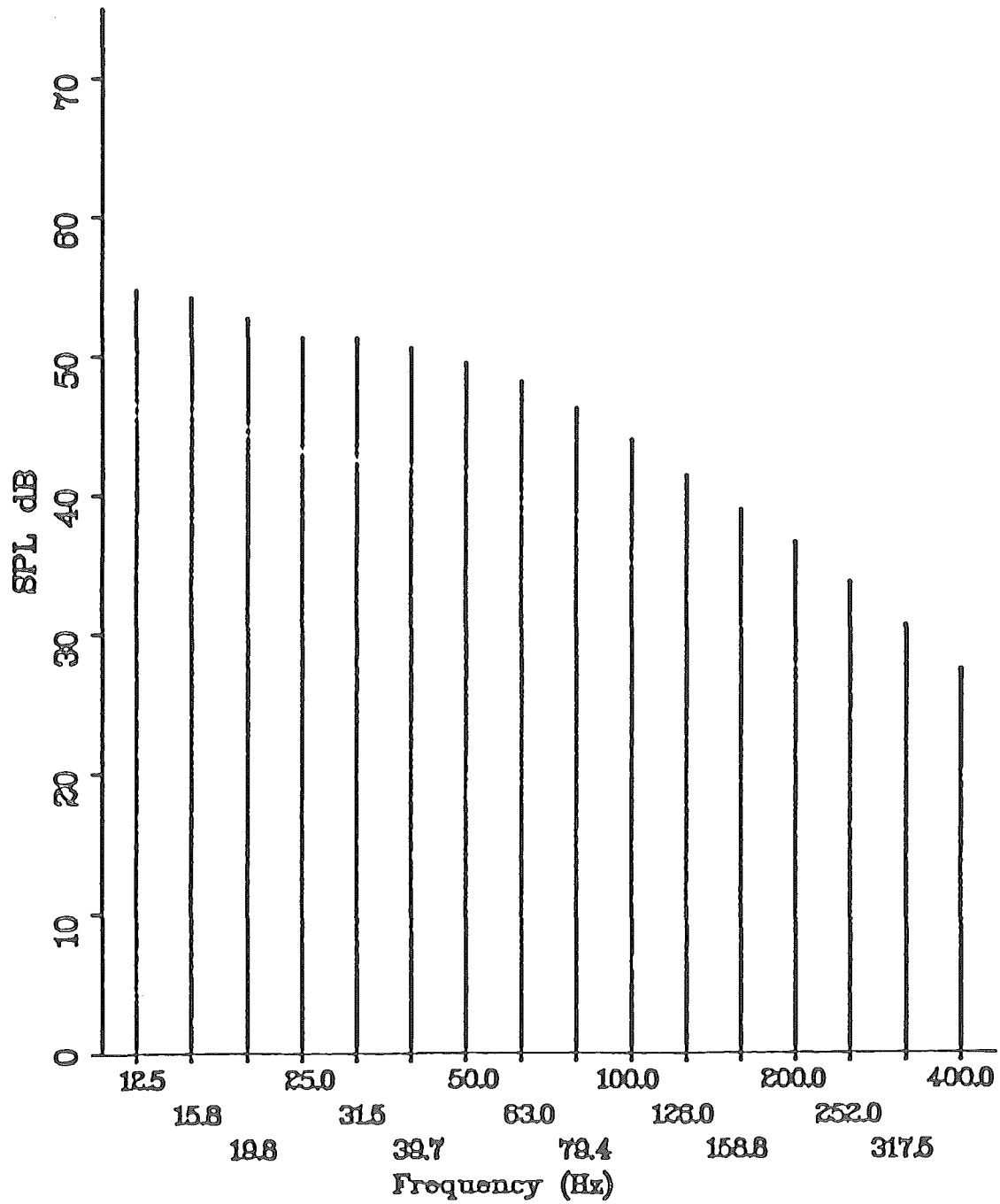
OASPL=0.635E+02 dB

Omega = 0.417 Hz   Uc =   7.5 m/s   R=   144. m
Psi =   147. Deg   F1 =   160. Deg
Roughness= 0.060 m
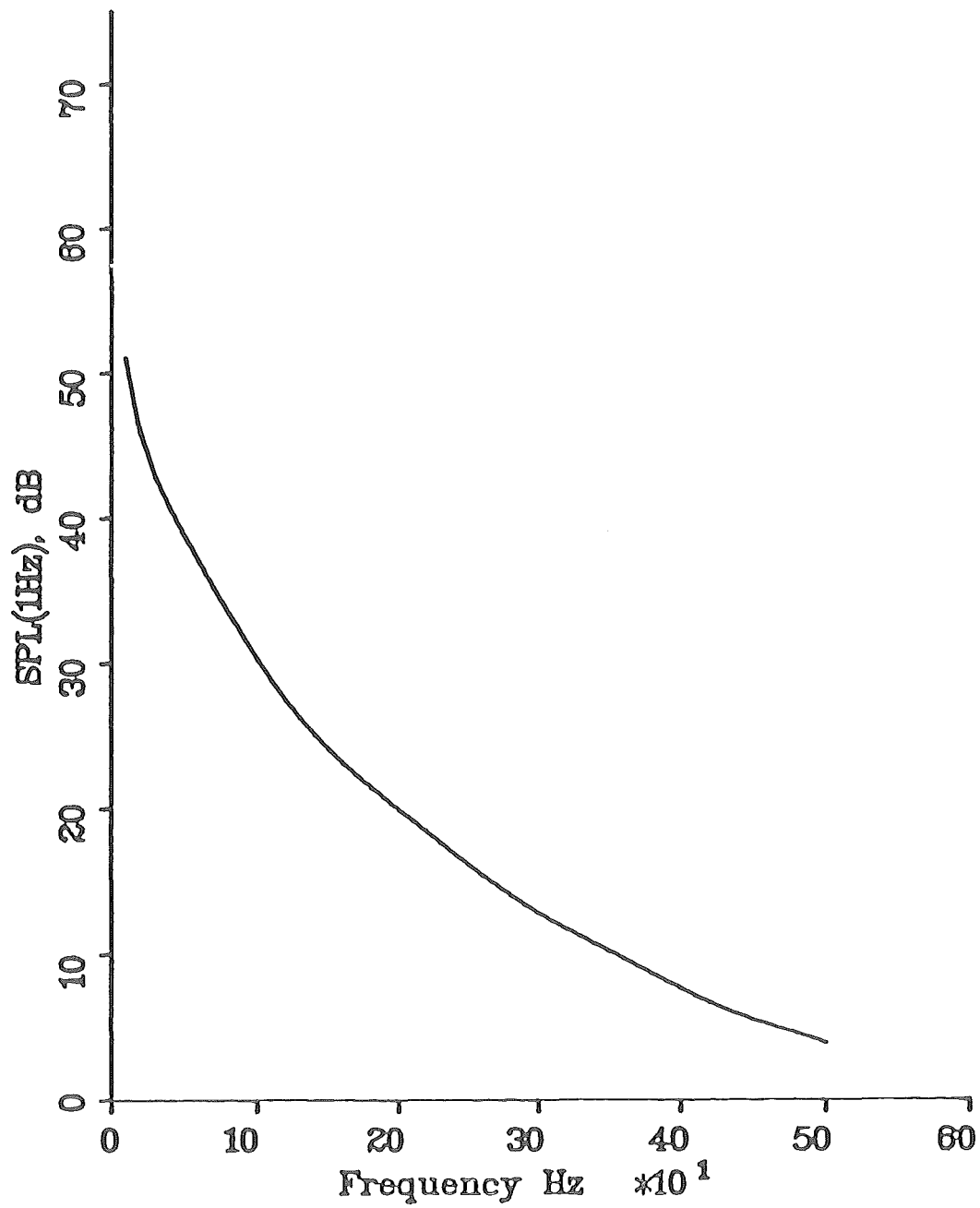
Blade Tower Passage Noise

WIND SPEED LEVELS IN THE WAKE OF THE MAGLARP WIND TURBINE TOWER AT X/D=2.3

$\bar{U}/\bar{U}o$ $\bar{U}o=$ 9.6
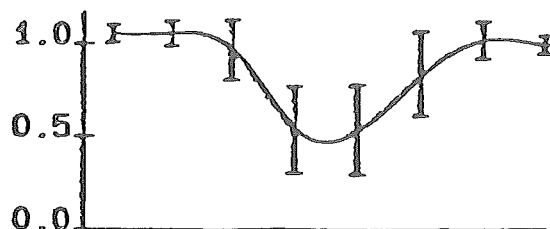
MEAN (HOTWIRE) WIND SPEED
WAKE PROFILE AVERAGED DU-
RING 12.8 SECONDS AND
NORMALIZED WITH REFERENCE
SENSOR MEAN WIND SPEED
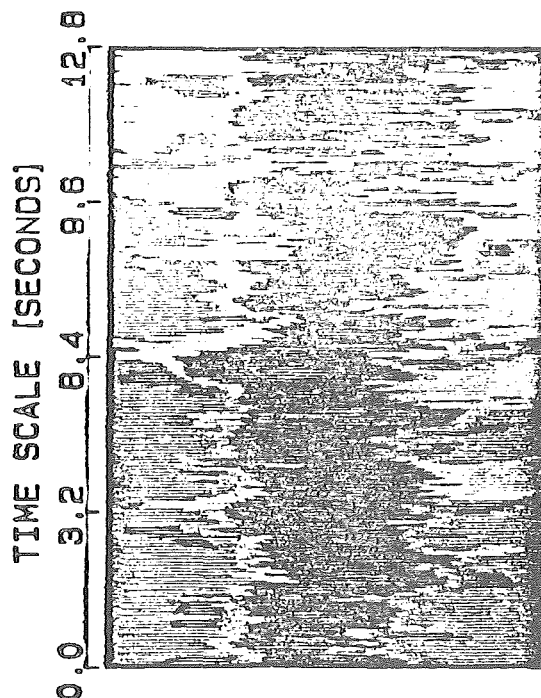
WIND SPEED LEVEL CHART
BUILT UP BY CONSECUTIVE
INSTANTANEOUS WAKES AVER-
AGED DURING 0.064 SECONDS

WIND SPEED   COLOUR
LEVELS [m/s]   KEY

11.2
REFERENCE MEAN: 9.6
8.0
6.4
4.8
3.2
1.6
LOWEST SPEED: 0.0

TIME SCALE [SECONDS]
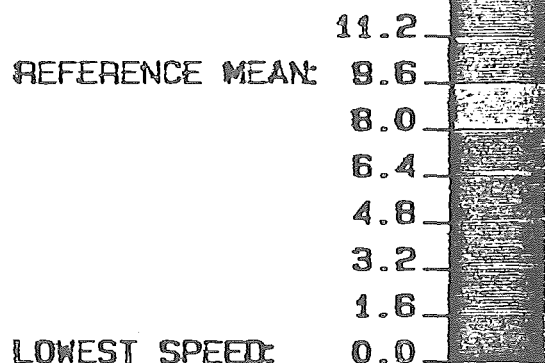
LATERAL POSITION OF THE
HOTWIRE SENSORS

REFERENCE
SENSOR Uo

D=3.9

X

DOWNSTREAM DISTANCE TO
THE SENSORS X=9.1 [m]

POSITION OF THE LADDER

Y10B01088.084
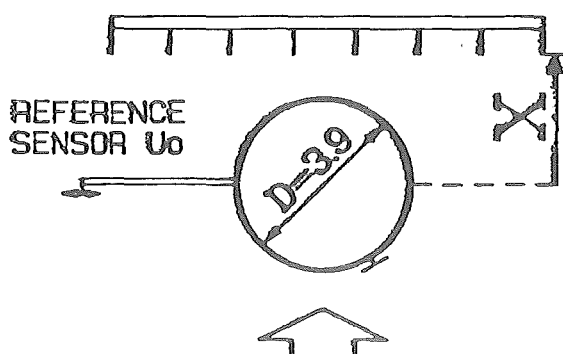
Computation of Blade Tower Passage Noise

Description of tower wake

Calculation of unsteady blade loading
using linearized aerofoil theory

Far field sound calculation

Impulsive sound due to the passage of the
rotorblades through the tower wake

Towerradius = 1.9 m

Rotorradius = 39.0 m

Number of blades = 2

The blade force is calculated at 0.75*R
where the chord is 2.00 m

Tower-wake velocity deficit

Direction of blade movement $\longleftarrow$
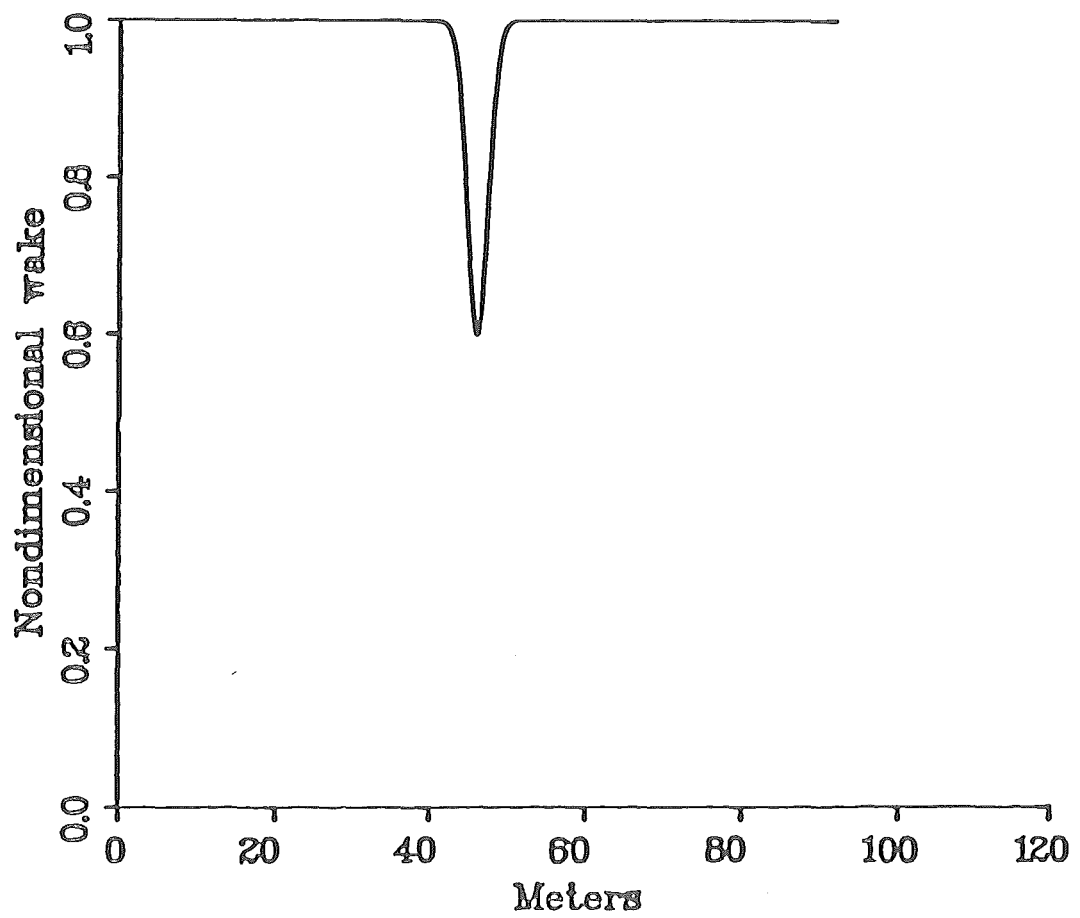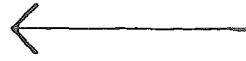
Time signal at a distance of 0.12 km from the rotor

RPM = 25.0
Wind speed = 7.5 m/s
Peak pressure = 0.973E+02 dB
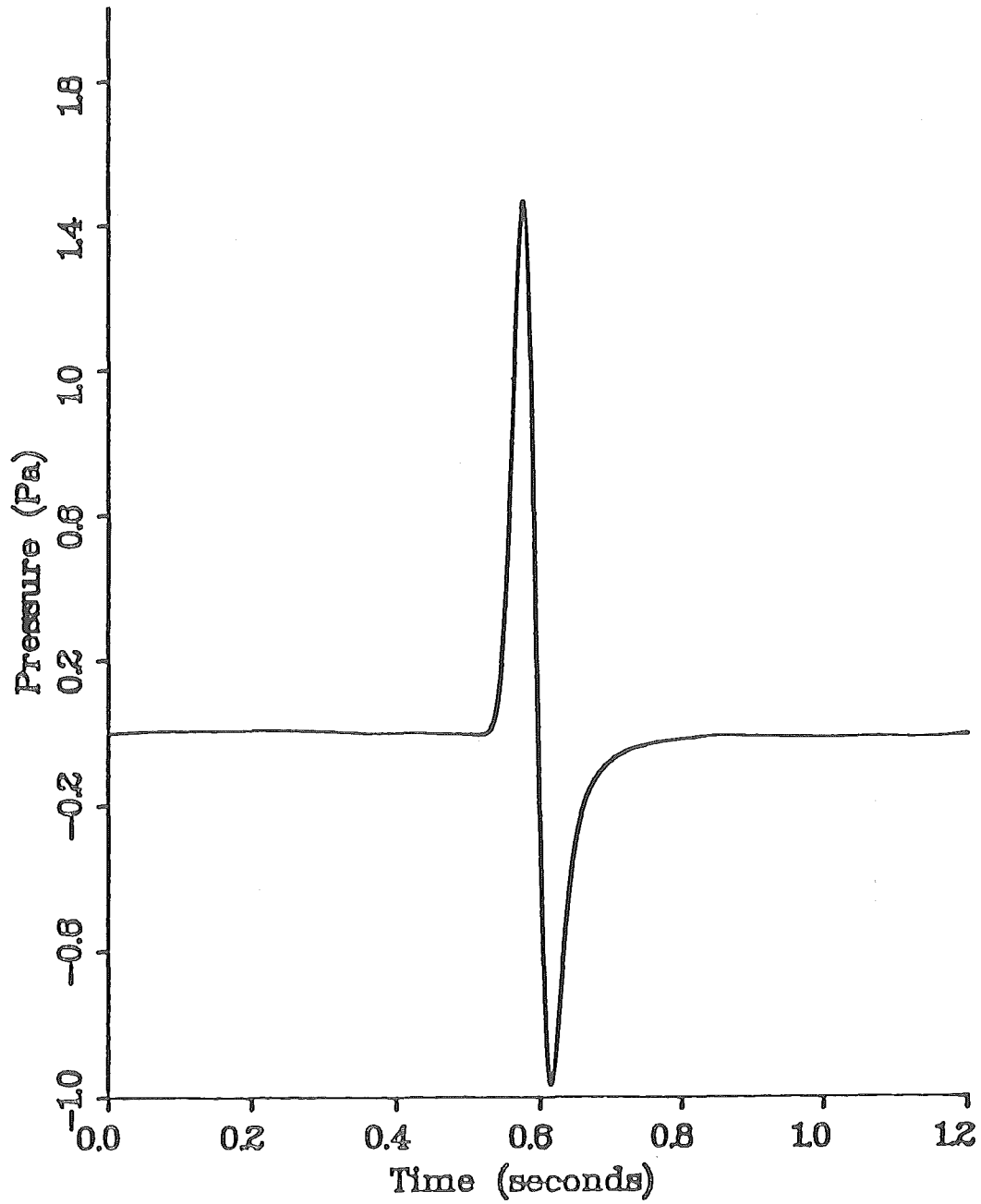
Sound pressure level for the
Fourier components of the time signal

RPM = 25.0
Windspeed =   7.5 m/s
Distance to observer =   0.12 km

OASPL=0.820E+02 dB
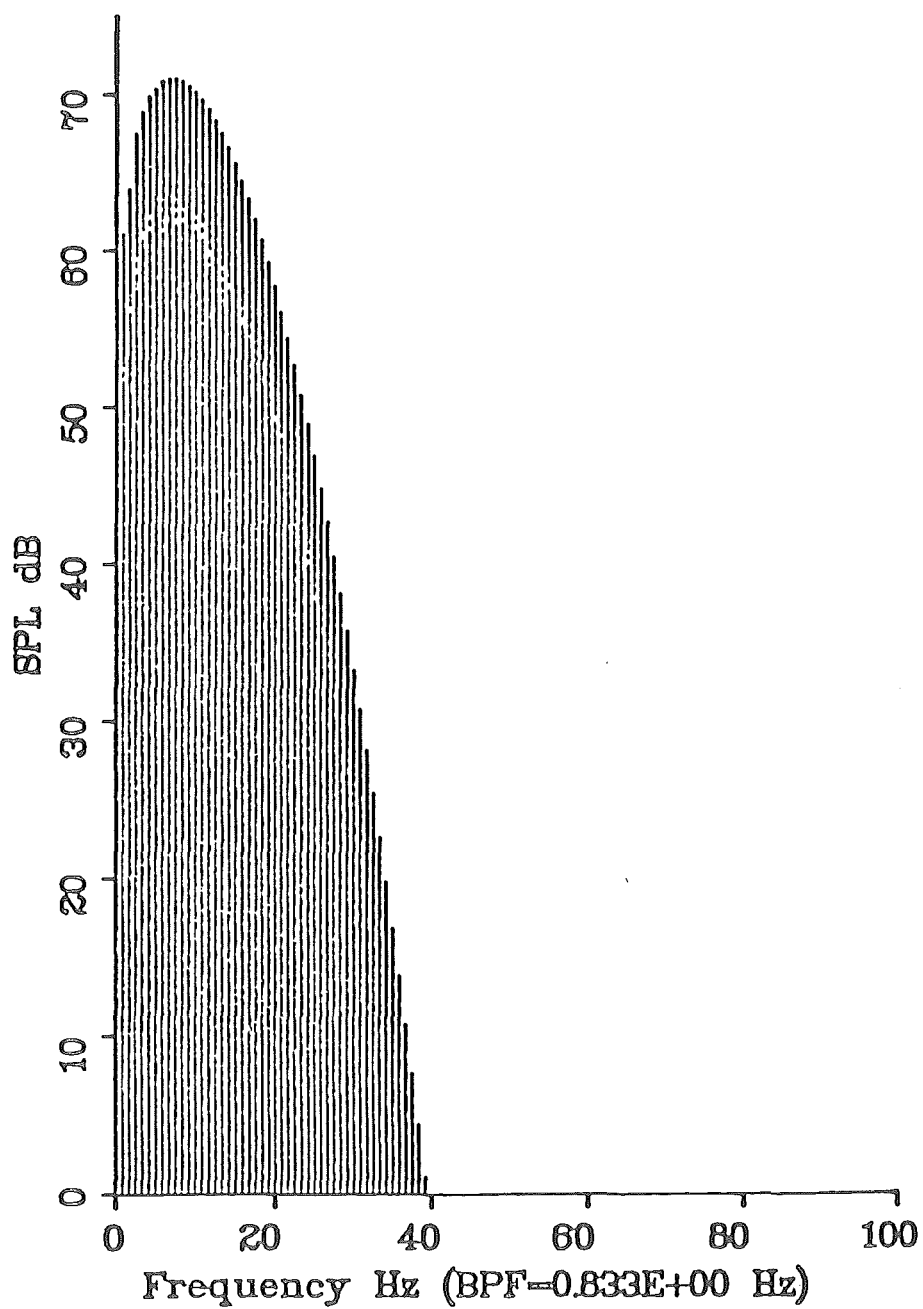
Frequency Hz (BPF=0.833E+00 Hz)

Sound pressure level in 1/3 octave band

RPM = 25.0
Windspeed = 7.5 m/s
Distance to observer = 0.12 km

SPL dB
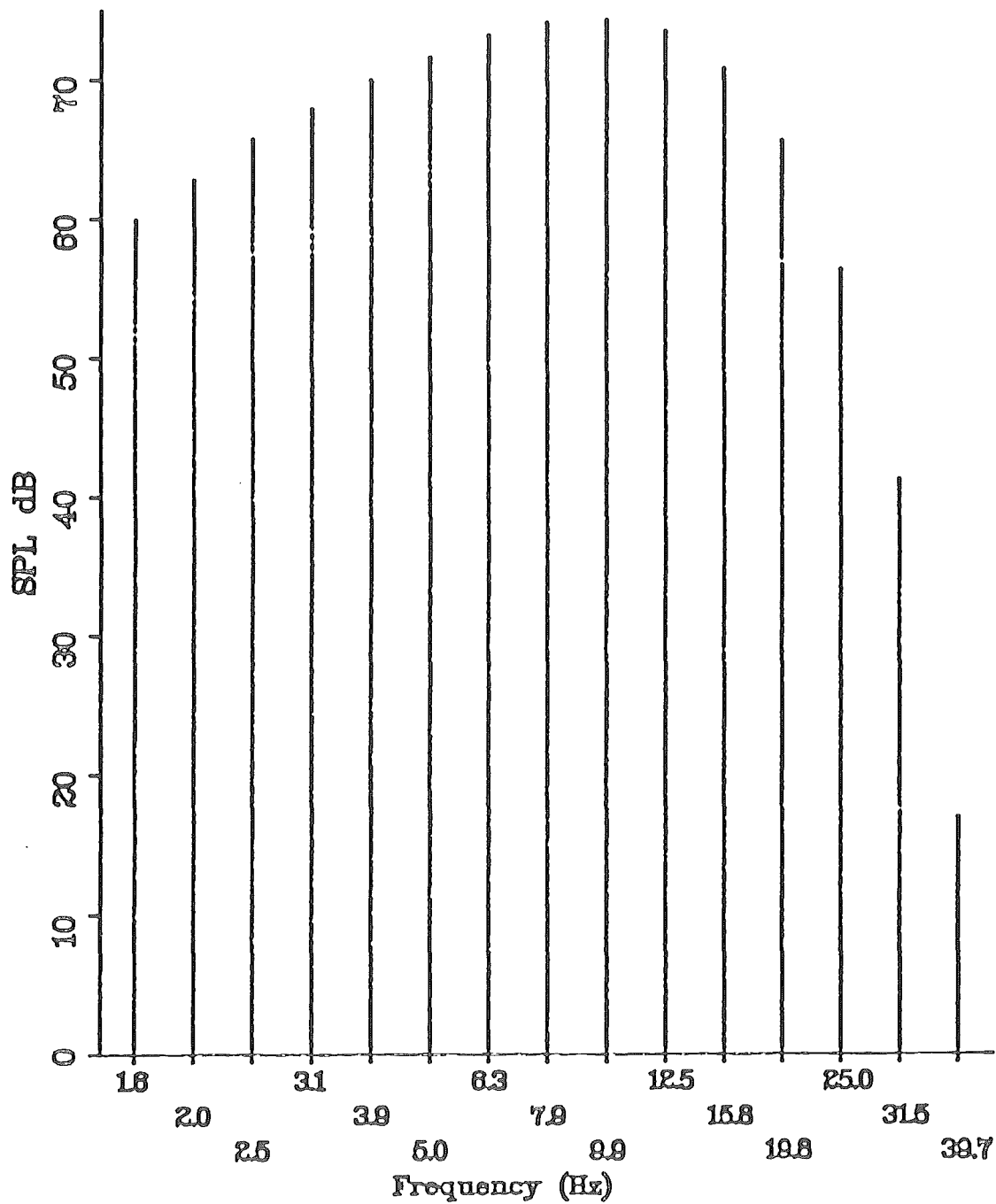
Frequency (Hz)

Parameter Influence on Noise Levels

Blade Tower Passage Noise

$\triangle$ Peak pressure $= 20*\log((V-v)/(V-v)ref) + 40*\log(N/Nref) +$
$$+ 60*\log(D/Dref) + 13*\log(C/Cref) - 12*\log(l/lref)$$

TBL-TE Noise

Peak frequency at : $f*d/U = St = 0.3$

Flat plate boundary layer $\rightarrow$ $d = 2.57*C*C_D$

$$f = 0.12*U/(C*C_D)$$

$\triangle Lw = 10*\log(n*C*D*C_D) + 50*\log(U)$

V	Wind velocity
v	Tower wake welocity
N	Rotational speed
D	Rotor diameter
C	Blade chord at 70% radius
l	Tower wake width
f	Frequency
d	Trailing edge boundary layer thickness
C_D	Blade drag coefficient
n	Number of blades
U	Blade velocity at 70% radius
St	Strouhal number
Lw	Overall sound power level

Correction of dBA values for background noise.

Suggestion: $\triangle L = 40 * \log(V/5)$

V   Wind speed at height 10 m.

Measured sound levels at different wind speeds
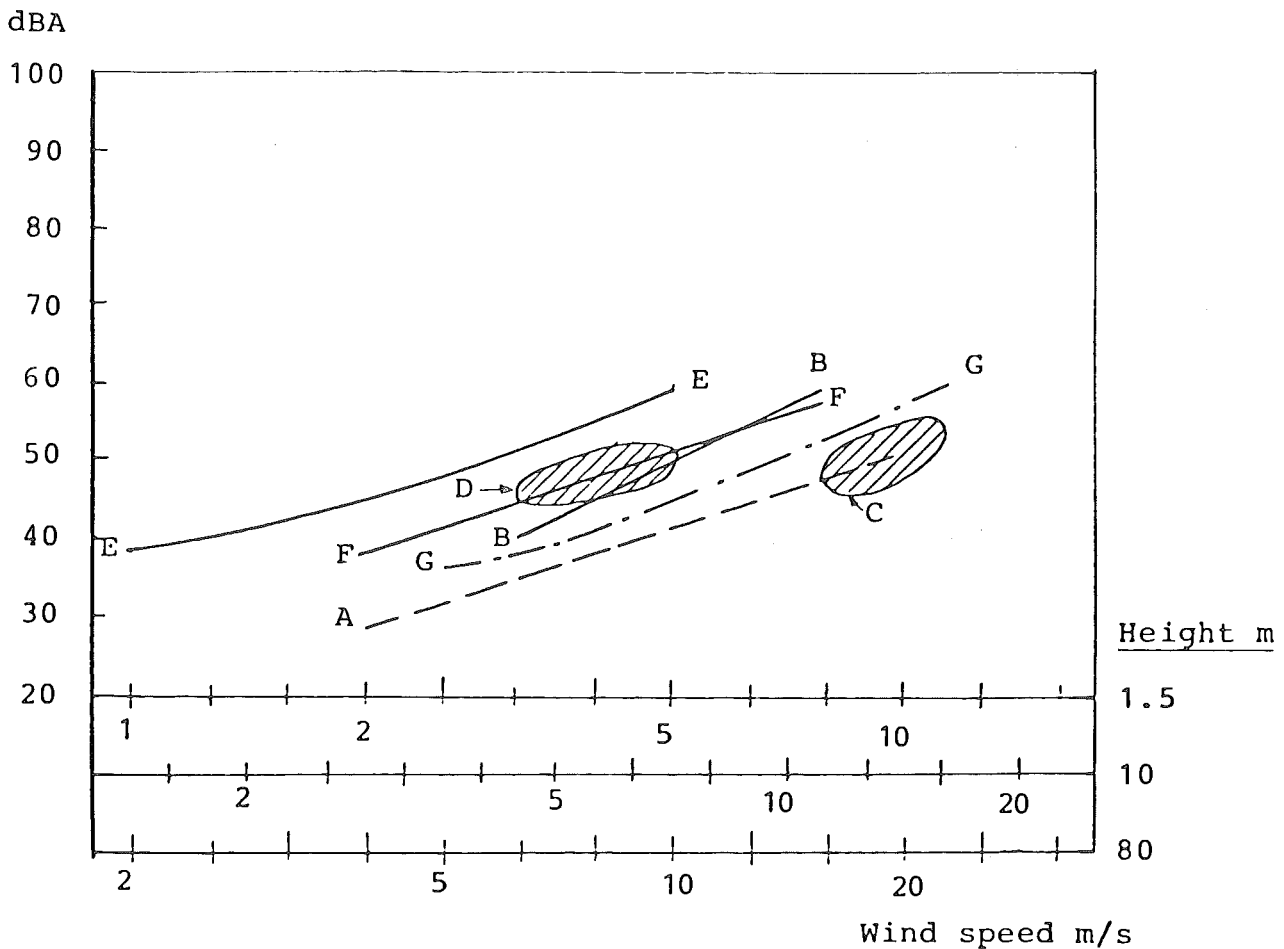
A = Self noise in Brüel & Kjaer microphone plus wind screen
    UA 0207.   Height 1.5 m

B = Close to vegetation. Ref. [20]

C = Open terrain. Ref. [21]. Probably at 20 m height

D = Mixed: open terrain and forest. Ref. [4]

E = Close to trees. Ref. [22]. Rustling of leaves

F = Open terrain. Ref. [23]

G = Possible choice for "Lowest Background Level"

Running Maglarp With Variable RPM

V80 $\geq$ 11 m/s   RPM=25

V80 $\leq$ 11 m/s   Constant tipspeed ratio

V80   Wind speed at height 80 m

Increase in energy production   2 %

Suggested correction to dBA value for background level

TBL-TE noise level .Variable RPM operation

Blade tower passage noise level . Variable RPM operation

Constant RPM operation
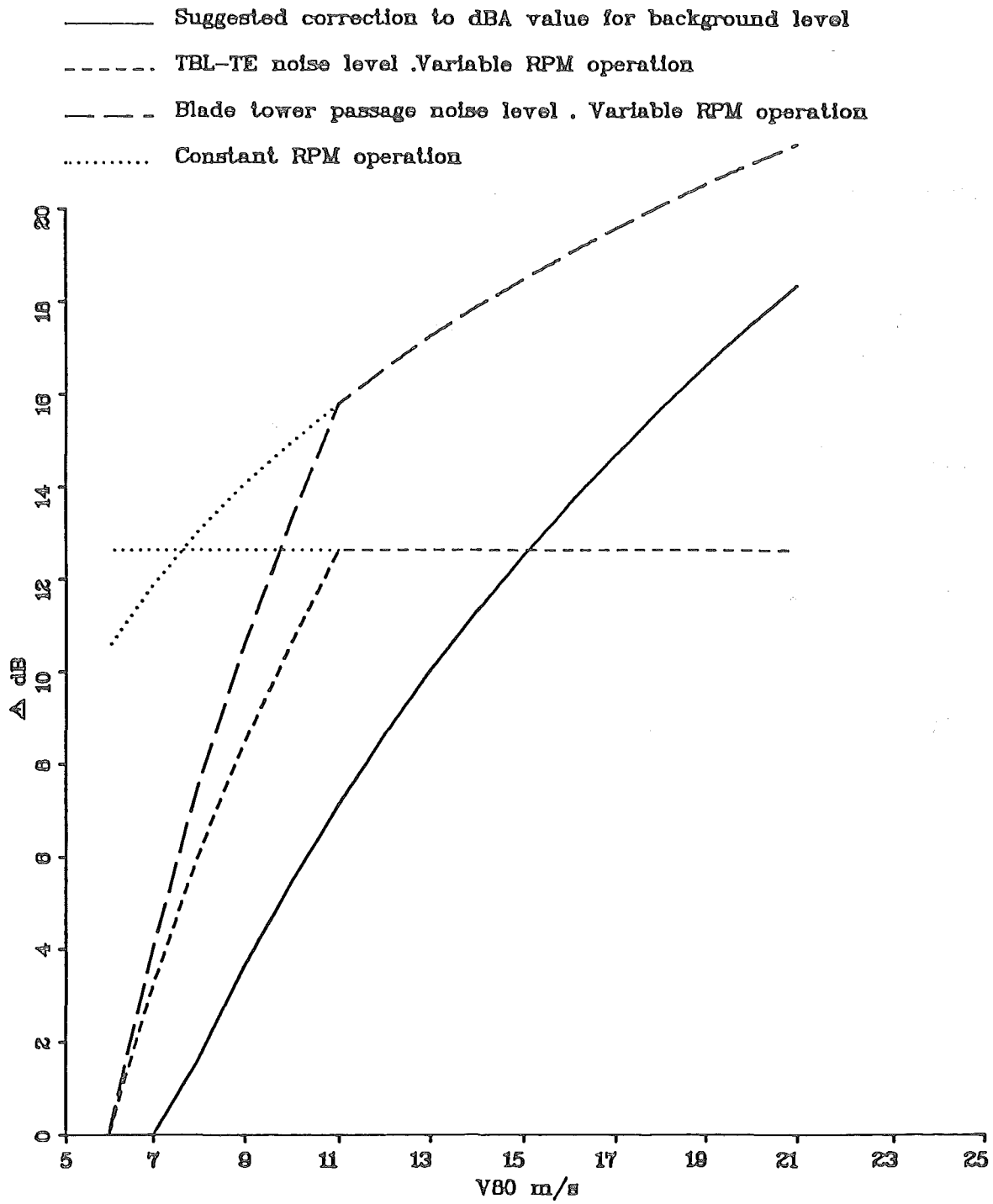
Conclusions

1. Prediction tools for blade tower passage noise seems to predict noise emission reasonably well

2. Prediction tools for high frequency noise are not sufficient

3. Reliable noise measurements for different machines are needed

4. It is important to take background noise levels into account when noise criteria are decided

5. Noise emission is highly dependent on rotational speed and running a turbine with variable rpm will lower the noise emission for low wind speeds

Environmental aspects of large-scale wind-power systems in the UK

A. Robson

Abstract: Environmental issues relating to the introduction of large, MW-scale wind turbines at land-based sites in the UK are discussed. Areas of interest include noise, television interference, hazards to bird life and visual effects. A number of areas of uncertainty are identified, but enough is known from experience elsewhere in the world to enable the first UK machines to be introduced in a safe and environementally acceptable manner. Research currently under way will serve to establish siting criteria more clearly, and could significantly increase the potential wind-energy resource. Certain studies of the comparative risk of energy systems are shown to be overpessimistic for UK wind turbines.

1 Introduction

Wind power is generally seen to be a clean and benign source of energy conferring little risk and substantial benefits, once installed, in the way of 'free' fuel. There is some awareness of possible problems following publicity over noise from certain types of machine in the USA, but, in the main, wind energy maintains the cosy image of the traditional Dutch-style windmill. Not so much a machine, as a homely looking structure which supplies the very bread we eat.

There is an enormous demand for electricity in an industrialised country such as the UK, and it is impossible to meet this without some environmental impact, whatever form the fuel may take. Wind power, although potentially a large energy resource, is a very dilute form of energy. Thus, wind turbines for electricity generation will have to be very big, and we will need many of them if they are going to be exploited seriously for electricity generation. 'Big' implies towers which are perhaps 200–260 ft overall height, with moving blades up to 300 ft across. It would need of the order of 650 such machines to supply electricity for 1 million people.

Given this scale of operation it is not surprising that wind energy is being approached by electricity utilities in a manner just as rigorous, economically and environmentally, as that applied to any large fossil or nuclear power station. One big advantage of wind over other fuels is that machines can be introduced one by one in relatively small energy units, so there is scope for learning as the programme develops.

One method of diminishing the general obtrusiveness of wind turbines it to locate machines in coastal waters and bring the power back to land by cable. However, engineering and maintenance difficulties add cost penalties to this approach, and the prospects for land-based turbines are well worth investigating. This paper will concentrate on the environmental aspects of these machines. Long-term prospects in the UK depend to a great extent on public reaction to the large machines which are planned to be installed in the next few years. The range of potential effects on the physical senses and the environment are discussed, in turn, in the following Sections.

2 Electromagnetic interference

Interference with television and other electromagnetic communication systems is a possibility with wind turbines, as it is with other tall structures. Because of this, positions within 100 m [1], and possibly as much as 1 km [2], of the line of sight between microwave communication links will have to be avoided as wind-turbine sites.

As far as the general public is concerned, it is impairment of TV picture quality which would impinge most of their awareness. Possible forward- and back-scatter television interference has been discussed by Sengupta and Senior [3]. The former produces varying brightness within a narrow sector behind the wind turbine. The latter is manifested over a wider angle, mainly to the side of the turbine and back towards the transmitter. Ghost images are produced, their intensity modulated by turbine blade movement. Directional receiving aerials can be used to reduce the possibility of scattered images, as discussed by Cavcey and Lee [4].

TV interference is most likely in areas where there is a weak signal because of the distance from the transmitter, where existing reception is none too good because of surrounding hills and where the wind turbine is exposed in a good position to receive and scatter interfering signals. Time lags between scattered and direct signals contribute to the noticeability of scattered images.

Degree of impairment of a TV signal has been classified on a five-grade scale by the Comité Consultative International des Radio-Communications (CCIR) [5]. Grades range from imperceptible (grade 5) through perceptible but not annoying (grade 4) to slightly annoying (grade 3), annoying (grade 2) and very annoying (grade 1). Depending on time delays and existing reception conditions, a wind-turbine-induced change in grade could lead to the necessity for remedial measures. The CEGB seeks the advice and co-operation of the British Broadcasting Corporation in assessing such effects. Potential protective measures, in addition to directional aerials, include relay stations and wired systems.

The area around the Burgar Hill site for the MW-scale wind turbine to be installed by the North of Scotland Hydro-Electric Board has been identified as being susceptible to interference, partly because of the borderline quality of the existing reception [6]. Following tests around the CEGB machine sites at Carmarthen Bay (installed) and Richborough (planned), it is considered

unlikely that these installations will cause problems (Black [7]), although TV reception tests will be carried out after installation to confirm this conclusion. For planning purposes, Eaton et al. [6] describe a method for estimating interference when measurements are not available. It can also be used for initial estimates of the effect of several machines.

Areas close to transmitting stations require special care. Studies in the Netherlands [1] suggest that an area of about 6 km radius around a broadcast transmitting antenna should be kept free of large reflecting obstacles, otherwise the antenna pattern is distorted.

3 Noise

3.1 Noise generation and progagation

Wind-turbine noise depends on machine power and size. It falls into two distinct categories. Enough is known about each category to be able to determine the minimum separation distance between a turbine and nearby housing necessary to avoid nuisance to the public. A margin is incorporated into these calculations to cover areas of uncertainty, such as the masking effect of local wind-generated background noise. When the uncertainties have been resolved, it may be possible to locate wind turbines closer to houses than would be considered appropriate at present.

The first noise category is mechanical noise from the generating equipment, gear box and linkages, which is considerable by conventional sound-proofing techniques.

The second type of noise is aerodynamic in nature, produced by blade motion, and is less amenable to treatment by conventional methods. One component of this is broadband noise, which ranges up to several kilohertz and produces a rhythmic 'swishing' sound. The other component has led to public complaint in the USA and is very-low-frequency noise and infrasound. The latter comprises pressures changes which fall below the normal detection limit for the human ear, at some 16–20 Hz, but, nevertheless, can induce adverse symptoms in susceptible individuals and lead to complaints. These low-frequency (LF) vibrations propagate particularly well through the atmosphere, and have been known to cause uncomfortable resonance effects in buildings several kilometres away. 'Thumping' noises are reported, particularly inside rooms which have a window facing the turbine. The problem is associated with the type of HAWT which has blades mounted downwind of the tower, so that they periodically chop through the tower wake. Kelley et al. [8] suggest that community annoyance by LF vibration is unlikely to arise if peak coherent radiation, at a distance of 1.5 rotor diameters, is simultaneously at or below 55–65 and 45–55 dB sound pressure levels in the 8 and 16 Hz octave bands, and under 35–45 dB in the 31.5 and 63 Hz bands.

The majority of wind turbines are horizontal-axis devices with upwind rotors. In this case the low-frequency noise does not occur to the same extent, and the broadband noise is also of interest. A source of noise on rotors with tip pitch control will be vortices shed at the junction with the main blade. Noise levels observed around one of these machines, the USA MOD-2 2.5 MW system, amounted to about 65 dB(A) at 130 m [9] corresponding to about 55 dB(A) at 400 m (wind speeds = 7.6–13.4 m/s). Local factors which influence noise propagation are vertical temperature and wind-speed gradients, diffraction by obstacles and absorption at the ground. Wind speeds increasing with height, as they normally do, tend to bend the propagation path; upwards upwind and downwards

downwind. Thomson [10] stresses the importance of meteorological factors and the desirability of simultaneous measurement of these in propagation experiments. Meteorological changes in the first few kilometres of the atmosphere have been found to produce noise shadow zones or enhancements of sound pressure level at distances of up to 15 km from the source. A useful general computer program for predicting noise propagation is discussed by Marsh [11].

3.2 Noise measurement, analysis and assessment

Wind turbines raise special problems for noise measurement and nuisance assessment due to the special character of the noise spectrum, the extra background noise produced by the wind and the problems of identifying a randomly varying sound source, the turbine, against this randomly varying background.

Traditionally, noise measurements for assessment of public complaint involve recording of sound pressure levels (SPLs) integrated across a standardised bandwidth, such as the octave filter band and weighted (as with dB(A)) so that the parameter recorded will be indicative of human response. Used in this way the measurement attempts to incorporate two effects, i.e. the physical response of the ear to pressure changes and the reaction of the individual to these sensations. For wind turbines these standard weightings may not be completely appropriate.

Impressed sounds are most noticeable when background noise is low, so potential community nuisance is often assessed relative to some fairly low background level, such as L_{95}, the noise level exceeded 95% of the time at the location concerned. Such levels are likely to occur at night, when noise generating activities are low and winds tend to be light. Since wind turbines operate in relatively strong winds, special evaluation problems are posed relating to the masking effects of background noise.

Wind-noise background SPLs and spectra are influenced by local buildings and vegetation. Noise around trees and bushes depends on the number and relative location of specimens and varies seasonally with leaf cover. Sites close to the sea shore pick up wave noise, which is very dependent on wind speed. Rainfall noise is intermittent, depends on the nature of the local surface and will be louder if the rain is wind driven. Soderquist [12] reports differences of about 15 dB(A) between open sites and positions close to trees (no rain). At all sites, noise increased by about 12 dB(A) for every doubling of wind speed above 5 m/s, and it was suggested that permissible wind-turbine noise levels should be increased systematically to allow for this effect. Miller [13] produced nomograms for deriving 'A' weighted sound levels in the open, or around trees during rainy, windy weather. Noise increased by 22 dB(A) as rainfall changed from 0.02 to 3.2 cm/h and wind speed from 0 to 16 km/h.

Another problem in this type of study is noise induced in the measuring system microphone. Standard wind shields are supplied for fitting to microphones, but they have limited value in high winds and additional measures are under investigation. Possibilities include mounting microphones closer to the ground, where wind speeds are lower, or above an artificially smooth surface. Advantages of the order of 10 dB(A) seem possible [14]. Electronic compensation (cross-correlation methods) using more than one microphone are another possibility.

The best method of collecting data for a wide range of wind speeds is to leave a recording system at a fixed site for an appropriate length of time (days—months). If wind direction is recorded, turbine noise directivity can also be

assessed, since the horizontal-axis turbine rotates to follow the wind direction. A system of this type has been developed by Nairne [14] for measurements of background and machine noise at CEGB wind-turbine sites. This approach contrasts with the usual method, i.e. making occasional visits to a site to take a series of measurements, each a few minutes long, at a number of points around the noise source. The operational difficulties of covering a comprehensive range of wind speeds in this way are apparent, though it has the advantage that mains power supplies are not needed.

The CEGB system uses two commercially available outdoor microphone units, one (2–50 Hz) for infrasonic noise and the other for broadband noise (50–10000 Hz). The use of two channels was found necessary to accommodate the large signal dynamic range (approximately 60 dB) produced in this wide frequency band over the range of wind speeds of interest.

In order to optimise data collection, the system employs a microsampling technique controlled by a microprocessor, which is capable of controlling sample rate dependent upon other input parameters: in this case wind speed. For wind-related background-noise measurements it transpired that samples of 10 s duration at a rate of 1 per hour below 5 m/s wind speed and 6 per hour at higher speeds produced a sufficient spread of data points to be statistically significant. For each sample, analogue noise recordings are obtained together with digital data of noise (in dB(A) terms), wind speed and direction, machine yaw angle (i.e. deviation from wind direction), rotor speed and electrical load, to investigate the noise emission characteristics from the aerogenerator. Both analogue and digital data are stored on magnetic tape for subsequent spectral and statistical analyses.

So far, noise background data has been recorded at two locations; one near a building and one over open grassland near the CEGB's experimental wind turbine at Carmarthen Bay [15]. Some very interesting results have been obtained. Background varied by about 30 dB(A) over wind speeds of 3–15 m/s, which is the operating range of the wind turbine. Human activity at this location appears to dominate noise SPL below wind speeds of 6 m/s, but winds control the background noise above that speed. Both sonic and infrasonic records showed background sound levels can vary significantly at, ostensibly, the same wind speed. Standard deviations of 10 s samples ranged from 8 dB(A) at low speeds (3.5 m/s) to dB(A) at high speeds (11 m/s).

For siting calculations it is necessary to establish the audibility of wind-turbine noise. Some noise sources have particular tonal characteristics which make them especially noticeable to the human ear, although there are differences from person to person. It is possible that the rhythmic variation of wind-turbine noise falls into this category. Stephens *et al.* [16] determined detection thresholds for low-frequency impulsive noise and broadband noise, confirming that detectability could not be predicted on the basis of overall measures such as dB(A). Because of amplitude modulation, the broadband noise from the MOD-2 machine was identified by human observers in any one-third octave band at a signal/noise ratio of 0 dB. Detection thresholds were established, but the usefulness of the data may be limited to situations where background noise spectra are similar to the two used in the study. The role of differential cognitive responses to noise has led Benton and Leventhall [17] to question the traditional noise assessment criteria. This is particularly relevant for low-intensity noise sources.

The degree of uncertainty in this and other areas does not mean that wind turbines cannot be located with a high degree of confidence at present, since a safe margin can be estimated from early machines. As the uncertainty is removed, with more research, it should be possible to position machines closer to residences than can be proved to be acceptable at present. This could increase the available wind resource significantly.

Another topic currently being debated concerns the best way to categorise noise emission from wind turbulences. Normally, the sound pressure level, or derived sound power level, at a radius not too far from the source would be reported. The variable character of wind-turbine and wind-induced background noise, however, means that averaged noise data may be of limited value for assessment purposes. Nairne [15] suggests that wind-turbine noise reports should include a measure of the noise variability as well as average values at a given average wind speed.

4 Visual effects

Megawatt generating wind turbines are large structures which would be visible over a wide area in some locations. Blade rotation will make them particularly noticeable. It is generally accepted, e.g. Sorensen [18] and Taylor [19], that machine design and the way they relate to their surroundings are important factors with regard to their acceptability as part of our environment.

The traditional Dutch style of windmill was favoured by the public in an American study [20], but is not suitable for efficient large-scale machines. In practice, these are much more slender and 'technological' in appearance, though this does not mean that they are necessarily inelegant or unappealing to the eye.

A variety of characteristics can be adjusted to modify the visual effects of wind turbines including, and possibly depending on, the landscape in which they are set. Design or siting considerations relevant to individual machines are scale, shape, colour pattern, rotation speed, reflectance of blade materials and how close the observer stands. Technical constraints will, of course, place a limit on how much some of these can be modified, but current design management, integrating the contribution of the individual designer with the technical engineering development, should result in a satisfactory aerodynamic design aesthetic. In an array of turbines the number of machines per group can be varied as well as separation distances, individually and between groups, and layout pattern. There may also be scope for screening sensitive vantage points if the local landscape does not contain enough screening elements.

Dearden [21] suggests that the general public can play a useful role in judging the relative merits of different landscapes. A certain amount of assessment work along these lines for landscapes with wind turbines has been carried out in the USA and Scandinavia using simulation methods. Turbine blade rotation needs to be taken into account, and an effective, and relatively cheap, simulation technique for close-up pictures, i.e. from a few hundred metres, is to film a working model placed close to the camera but against a real landscape [22]. To simulate wind turbines as seen from greater distances, video recordings of models have been electronically mixed into video films of different landscapes.

Swedish researchers [1] using simulation, together with other methods, defined zones of decreasing visual effect at increasing distances from a large wind turbine. Machines were particularly intrusive at distances up to about three

68

times their height. They also dominated a sector of the field of vision at distances up to ten times their height. At longer distances machines were noticeable but perceived as belonging to the distant landscape. In theory, they are visible at very long range, e.g. 40 km for a 100 m turbine, but, in practice, visibility is frequently restricted by topography, vegetation and weather. Techniques employing digital computers and photogrammetric methods from aerial photography [23] are available for delineating areas from which a particular structure would be visible.

The experiments confirm that large wind turbines are more acceptable in some landscapes than others. In the USA wind energy was perceived by the general public as a clean energy source which should be encouraged as a matter of principle. Areas considered 'scenic' were therefore not necessarily excluded as turbine locations [20]. Open landscapes are more sensitive to visual intrusion than more enclosed or obstructed areas, but the Scandinavian work suggests that a landscape where wind power dominates without restriction may still be tolerated, having been re-evaluated by observers as a 'wind-power landscape' [1]. It is not clear how far these judgements reflect national geographical and sociological characteristics which limit their relevance in other countries. No information is reported on attitudes to colour, pattern and so forth for individual machines.

A case study for an array of 16 machines on the island of Gotland [24] considered conflicts with various preservation, residential and land-use interests, including visual aspects, for nine candidate sites. A coastal location was eventually favoured, machines being placed in two lines along a strip of land 4 km long and running parallel to the shore lines.

5 Bird life

All structures represent a potential collision hazard to bird life. Accidents involving large numbers of birds arise mainly in bad weather and around buildings or towers which support searchlight beams, such as lighthouses or airport 'ceilometer' towers. Strong lights appear to attract and disorientate migrating birds, and the deaths of large numbers have been reported [25]. There are several reasons why wind turbines are unlikely to produce such extreme effects, and experience to date supports this case. Local birds quickly identify new obstacles in their territory, and migrating wildfowl normally fly much higher than the tallest turbines envisaged. Migrating songbirds fly at lower altitudes, though still above turbine height. The risk of strikes is greatest when bad weather or low cloud force birds to fly lower than normal, although birds will usually choose good anticyclonic weather with clear skies for crossing areas such as the English Channel or North Sea [26]. There have been no recorded incidents of significant bird deaths at any large wind turbine to date.

Avery [27] concluded that small, steady losses due to collisions with ubiquitous objects are of far greater overall magnitude than episodic losses of birds at tall structures.

To investigate wind-turbine effects in more detail, American researchers [25] observed a small sample of birds approaching a turbine some 50 m tall. Two-thirds of these took avoiding action, the other one-third traversed the swept area without harm. Sorensen [18] suggests that blade movement will make turbines more noticeable than similar large structures to birds, making it relatively easy for them to take avoiding action.

The CEGB has adopted a policy of surveying early wind-turbine sites to confirm that bird-strike effects are

indeed small. The site of the first operational machine, the 200 kW 24 m diameter blade machine at Carmarthen Bay, is being surveyed regularly by a local ornithologist as agreed with the Nature Conservancy Council. The bay area is acknowledged as important because of its widely dispersed population of seaducks and estuarine wildfowl, waders and other birds [28]. No dead birds have been reported to date, although the period when the blades have been turning has been very limited because of operational problems. Similar arrangements are being made, via the Royal Society for Protection of Birds, for the machine of up to 4 MW and up to 90 m diameter blades for which statutory approval is being sought at Richborough in Kent. The nearby Pegwell Bay and the Stour river valley are seen as important landfall sites for migrating birds. Surveys of this type have to account for scavenging effects, since foxes and other scavengers soon discover new food sources in their locality. After an initial learning period the amount of scavenging can be related roughly to the time interval between survey visits.

Apart from being bigger than the Carmarthen Bay machine, the Richborough turbine will be located fairly close to the river Stour, which may be used as a bird migration route. Studies of bird collisions with overhead power lines have shown that they increase close to outstanding navigational features [27]. For this reason Richborough is, potentially, a relatively sensitive site. Effects
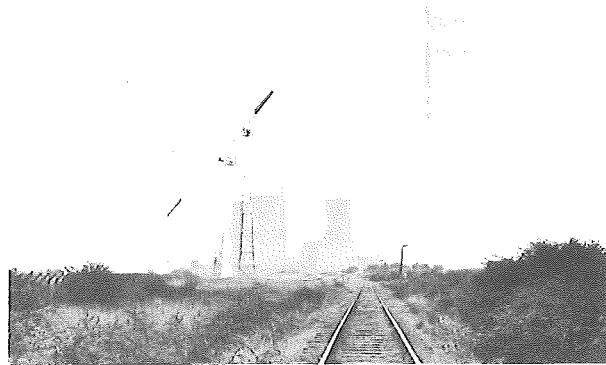
Fig. 1 *Typical megawatt-scale wind turbine on the proposed site at Richborough Power Station*

In this case, two additional masts are included to carry wind-measuring equipment for research purposes.

are still expected to be small, but the position will not be quantified until surveys have run for some time. A two-year survey programme is planned which should also provide data of value to future assessments.

6 Risk

Risks to people and property from projectiles and broken blade fragments are discussed by Ainslie *et al.* [29]. The wider issue of risks to workers and public due to provision, operation and maintenance of wind turbines has been the subject of a number of reports in the field of comparative risk analysis. Space limits the amount of discussion possible here, but the technique has been widely promoted as a process for making decision on safety matters in the energy industries and elsewhere. A Royal Society Study Group [30] has endorsed the basic approach, but pointed out that risk estimation is an inexact process of prediction. Risk analyses provide a useful input to the decision making process, but there is still a considerable role for political judgment that combines expedience with equity.

Data quoted for developing technologies such as wind power are likely to be particularly speculative. This can be illustrated by considering the various estimates for wind and other energy sources published by Inhaber [31–33], which have been strongly criticised by Holdren *et al.* [34] and others. Inhaber combines morbidity and mortality estimates to yield man days lost per megawatt year net output of electricity for different modes of generation. The analysis for wind power incorporates the impact of producing and transporting turbine materials. Estimated effects had been falling steadily from a range of 900–220 man days lost/MWy in November 1978 [31] to about 120–40 in November 1979 [32] and 90–28 at a meeting in November 1980 [33], i.e. an order of magnitude decrease in 2 years. As with risk estimates in other areas, it should be remembered that the range of values are not error bars in an empirical sense, but reflect a range of assumptions about factors such as 'how much concrete is needed?' as well as estimated health impacts (a controversial field) and industrial and public accident statistics for the USA, not the UK.

Morris [35] considers that the 1978 estimate of the upper limit was high by a factor of 29 for worker days lost and by a factor of 930 for public days lost. This implies that November 1980 data are still too high. Consideration of a few areas where UK data is available confirms that this is certainly the case for UK wind turbines. For example:

(*a*) the estimated annual load factor was increased from 14 [32] to 20% [33], but this is still less than likely values for UK lowland sites, i.e. 20–30% [36]

(*b*) machine lifetime is taken to be 20 years, whereas CEGB [37] assume 25 years for MW-scale machines and would aim to extend this period

(*c*) a proportion of the risk is due to air pollution from production of materials for the turbines or their associated backup or storage systems and from traffic accidents arising from movement of these materials. Inhaber's values for rail traffic are based on statistics for North America, which give risks up to an order of magnitude higher than the UK rail freight system. This is because of the better safety record of the latter and the shorter journeys involved on average in the UK. Estimates of air pollution effects vary widely. For example, values in the literature for deaths/GWy due to coal-fired electricity generating plant vary from 0 to 100 or more. UK reviewers Ferguson [38] and Cohen [39] favour zero or near zero values, whereas Inhaber [32] assumes 32 to 95 on the basis of American epidemilogical work which does not allow for a health damage threshold

(*d*) UK estimates of material requirements, 75 metric tons/MW, are only 70% of these used by Inhaber [33]

(*e*) backup system and storage account for about 62.5 and 3.5%, respectively, of the estimated wind-energy risk [33]. The CEGB already operates a large fully interlinked electricity network, which has a net capability of about 55000 MW and meets most of the electricity demand for England and Wales. Additional links are currently being installed across to France. On such a system the addition of a MW-size wind turbine is a marginal, in fact very marginal, activity and wind power is likely to remain marginal in this sense for a considerable time. Storage needs are considered negligible and backup plant to cover common mode unavailability, due to light winds over a wide area, exists already. Thus any additional risks on this account can be ignored, reducing the lowest Inhaber estimate by a further 65%.

The combined effect of these corrections, even ignoring

those under (*c*) above, is to reduce the lowest Inhaber estimate by almost an order of magnitude.

This illustrates the uncertainties in risk analyses and the dangers of taking figures from one study out of context. A much more promising technique than risk analysis is that of decision analysis as recommended by Watson [40] in the UK, building on the work of Howard [41] and others [42] at Stanford Research Institute in the USA.

The problem structuring employed in this methodology helps to clarify the issues involved, and it is possible to consider subjective judgments of risk levels as well as actual risk data. Cost-benefit elements are incorporated, and concepts such as 'opportunity costs' can be applied in both economic and safety spheres, i.e. how else would capital be invested, or what other health risks would be experienced by workers and public, if some alternative developments were carried out instead of a wind-power development?

The overall aim, whatever method is adopted, should be an energy system which has an impact judged acceptably low for that system, taking into account special features such as long-term fuel costs or resource availability. The Royal Society Study Group offer guidelines on risk acceptability, but stress that it is not possible to set universal criteria. From the regulatory point of view, each case must be regarded on its merits, and significantly different quantitative guidelines might well apply to different situations [30].

7   Conclusions

Enough is known about large wind turbines for them to be sited in a safe and environmentally acceptable manner on a limited scale on land in the UK.

Various research and development studies currently underway, plus experience with the first few machines, will help to establish the size of the land-based wind resource and for prospects for its wider utilisation by the electricity supply industry. The CEGB will spend time and effort to achieve an acceptably low environmental impact for wind turbines, but some intrusion on human activities or ecological conditions is to be expected, as it is with all types of electricity generation. At the end of the day it will be for the statutory organisations, environmental interest groups, the wider public and ultimately the Secretary of State for Energy, to judge whether this degree of intrusion is acceptable or not, hopefully bearing in mind the benefits of the electricity supplied.

8   References

1 PERSHAGEN, B.: 'Environmental and meteorological aspects of wind energy conversion systems'. Final Report of Task 1, International Energy Agency, Report NE 1981-25 (National Swedish Board for Energy Source Development, 1981)
2 MANNING, P.T.: 'The environmental impact of the use of large wind turbines', *Wind Eng.*, 1983, 7, pp. 1–11
3 SENGUPTA, D.L., and SENIOR, T.B.A.: 'Electromagnetic interference to television reception caused by horizontal axis windmills', *Proc. IEEE*, 1978, 67, pp. 1133–1142
4 CAVCEY, I.C.H., and LEE, L.Y.: 'Television interference due to electromagnetic scattering by the MOD-2 wind turbine generators'. IEEE Power Engineering Society Summer Meeting, 1983
5 CCIR: 'Directivity of antennas in the reception of broadcast sound and television'. CCIR Recommendation 419, 15th Plenary Assembly, 1982 11, (1), p. 236
6 EATON, J.L., BLACK, R.I., and TAYLOR, G.H.: 'Interference to television reception from large wind turbines'. BBC/IBA Engineering Research Report BBC RD 1983/2, March 1983
7 BLACK, R.I.: Private communication

8 KELLEY, N.D., HEMPHILL, R.R., and MCKENNA: 'A methodology for assessment of wind turbine noise generation', *Trans. ASME. J. Sol. Energy Eng.*, 1982, **104**, pp. 112–120

9 HUBBARD, H.H., SHEPHERD, K.P., and GROSVELD, F.W.: 'Sound measurements of the MOD-2 wind turbine generator'. NASA Contractor Report 165752, NASA Langley Research Center, USA, 1981

10 THOMSON, D.W.: 'Noise propogation in the atmosphere's surface and planetary boundary layers'. Internoise 82, San Francisco, USA, 1982

11 MARSH, K.J.: 'The CONCAWE model for calculating the propagation of noise from open-air industrial plants', *Appl. Acoust.*, 1982, **15**, pp. 411–428

12 SODERQUIST, S.: 'Swedish WTG's: the noise problem'. 4th International Symposium on Wind Energy Systems, Stockholm, 1982

13 MILLER, L.N.: 'Sound levels of rain and of wind in the trees', *Noise Control Eng.*, 1978, **11**, pp. 101–109

14 CHRISTIE, D.: Private communication

15 NAIRNE, P.: 'The measurement of background noise levels at the aerogenerator site, Carmarthen Power Station'. CEGB SW Region, Scientific Services Department, Report SSD/SW/82/N147, 1983

16 STEPHENS, P.G., SHEPHERD, K.P., HUBBARD, H.H., and GROSVELD, F.W.: 'Guide to the evaluation of human exposure to noise from large wind turbines'. NASA Technical Memorandum 83288, 1982

17 BENTON, S., and LEVENTHALL, H.G.: 'The effect of auditory processing on the development of low level low frequency noise criteria', *J. Low Freq. Noise & Vib.*, 1982, **1**, (3)

18 SORENSEN, B.: 'Wind energy' *in* El-HINNAWI, E., and BISWAS, A.K. (Eds.): 'Renewable sources of energy and the environment' (Tycooly International Publishing Ltd., Dublin, 1981), Chap. 4

19 TAYLOR, R.H.: 'Alternative energy sources for the centralised generation of electricity' (Modern Energy Studies Series, Adam Hilger Ltd., Bristol, England, 1983)

20 FERBER, R.: 'Public reaction to wind energy and windmill designs'. Wind Energy Conference, Washington, USA 1981

21 DEARDEN, P.: 'Public participation and scenic quality analysis'. *Landscape Planning*, 1981, **8**, pp. 3–19

22 ENGSTROM, S., and PERSHAGEN, B., (Eds.): 'Aesthetic factors and visual effects of large scale WECs'. International Energy Agency, Programme of Research and Development on Wind Energy Systems, Final Report of Task A5 NE 1980:20 (National Swedish Board for Energy Source Development)

23 HEBBLETHWAITE, R.L.: 'The determination of zones of visual influence by computer and photogrammetry'. CEGB Technical Disclosure Bulletin 255, 1981

24 BERGSJO, A., NILSSON, K., and SKARBACK, E.: 'Wind power in the landscape. 4th International Symposium on Wind Energy Systems, Stockholm, 1982

25 ROGERS, S.E., CORMABY, B.W., RODMAN, C.W., STICKSEL, P.R., and TOLLE, D.A.: 'Environmental studies related to the operation of wind energy conversion systems—final report'. Report C00-0092-77/2, US Department of Energy, December 1977

26 WILLIAMSON, K.: 'Weather system and bird movements', *Q. J. Roy. Met. Soc.*, 1968, **95**, pp. 414–423

27 AVERY, M.L.: 'Impacts of transmission lines on birds in flight'. Proceedings of Workshop at Oak Ridge, Tennessee, Report FWS/OBS-78/48, US Department of the Interior, 1978

28 RATCLIFFE, D. (Ed.): 'A nature conservation review. Vol. 1' (Cambridge University Press, London, 1970)

29 MacQUEEN, J.F., AINSLEE, J.F., MILBORROW, D.J., TURNER, E.M., and SWIFT-HOOK, D.T.: 'Risks associated with wind turbine blade failures'. *IEE Proc. A*, 1983, **130**, pp. 574–586

30 The Royal Society: 'Risk assessment'. Study Group Report, 1983

31 INHABER, H.: 'Risk of energy production'. Report AECB1119/Rev. 2 Atomic Energy Control Board, Canada 1978

32 INHABER, H.: 'Risk of energy production'. Report AEC51119/Rev. 3. Atomic Energy Control Board, Canada, 1978

33 INHABER, H.: 'The risk of producing energy'. Paper presented to Royal Society discussion meeting on the assessment and perception of risk, *Proc. Roy. Soc. London.*, 1981, **A376**, pp. 121–131

34 HOLDREN, J.P., ANDERSON, K., GLEICK, P.H., MINTZER, I., MORRIS, G., and SMITH, K.: 'Risk of renewable energy sources' a critique of the Inhaber report'. Report ERG 79-3, Energy Resources Group, University of California, Berkeley 94720, USA, 1979

35 MORRIS, G.: 'Problems and pitfalls in the environmental assessment of energy systems'. Report of the 1st International Conference on Health Effects of Energy Production, Atomic Energy of Canada Ltd., Chalk River, Ontario, 1979

36 TALBOT, J.: Private communication

37 WRIGHT, J.K.: 'CEGB proof of evidence on: alternative methods of electricity generation'. Sizewell 'B' Public Inquiry, CEGB P3, 1982

38 FERGUSON, R.A.D.: 'Comparative risks of energy generating fuel systems in the UK' (Peter Perigrinus Ltd., 1981)

39 COHEN, A.V.: 'Relative risk studies and their relevance to decision making: the analytical approach in perspective'. Sixth Annual Symposium, Uranium Institute, London, 1981

40 WATSON, S.R.: 'On risks and acceptability', *J. Soc. Radio. Prot.*, 1981, **1**, (4)

41 HOWARD, R.A.: 'The foundations of decision analysis', *IEEE Trans.*, 1968, SSC-4, (3)

42 NORTH, D.W., and MERKHOFER, M.W.: 'A methodology for analysing emission control strategies', *Comput. & Oper. Res.*, 1976, **3**, pp. 185–207

CENTRAL ELECTRICITY GENERATING BOARD
SOUTH WESTERN REGION
SCIENTIFIC SERVICES DEPARTMENT

A PROGRAMMABLE AUTOMATIC NOISE DATA AND OTHER RELATED PARAMATER
ACQUISITION SYSTEM (PANDORA)

by P J Nairne and M R Burt

SUMMARY

The study of noise emissions from Board installations often requires the
expenditure of considerable time and effort due to the vagaries of the weather,
operational uncertainties, interference from other sources and the need to
collect large quantities of data in order to describe noise environments in
statistical terms.

A microprocessor controlled sampling system has been developed and utilised
in field studies which permits the unattended collection of noise and other
related data, in digital and analogue formats, within programmable limits using
a range of control parameters. This report describes the capabilities of the
system with examples of its use and also indicates appropriate analysis
methods.

The major advantages of this system (PANDORA) over commercial "environmental
analysers" are the availability of analogue noise signals for source
discrimination, synchronised measurement of several parameters to study
relationships and the concentration of data collection during appropriate
periods.

1.   INTRODUCTION

Many noise problems associated with the Board's Power Stations and Transmission Systems require the collection of considerable quantities of data to establish the statistical variation of noise emission levels. Others require measurements to describe noise environments associated with particular operations, the timing of which cannot be precisely planned, or noise characteristics which are highly dependent upon climatic conditions.

In the past, this has meant that staff using portable measuring and recording equipment have spent long periods of time on sites awaiting particular events or suitable weather conditions. Due to the perverse nature of the British climate and the complexities of Board operations, this often meant that much valuable time and effort were wasted. This, together with the more stringent nature of noise legislation, led SWR-SSD to consider more suitable, automated methods of gathering noise data, see refs (1), (2), (3) and (4). Other organisations and instrument manufacturers were also aware of this situation and over the past few years a number of digital sound level measurement systems have become available. However, most of these systems have been designed with particular noise sources in mind (e.g traffic and aircraft noise) and tend to provide aggregated statistical data in a block format at prescribed times. Because, in most Board noise investigations it is necessary to discriminate between the contribution from our own and other noise sources, it was considered necessary to utilise analogue data, in addition to digital data, to permit aural and/or spectral analysis of the noise environment. In addition, "microsampling" techniques (i.e data only collected for a fraction of the total time) were employed to minimise data collection and consequent analysis effort.

The first generation of unattended noise measuring equipment were basic "microsampling" systems where timing was controlled by synchronous clocks which actuated tape and chart recorders via a series of relays. Later, simple triggering circuits were added to provide a further control parameter. With the advent of more powerful and cheaper microprocessor technology, the logical development was to employ such techniques in a noise measurement system which could be left unattended for long periods and which could be programmed to collect relevant data for a wide variety of noise environment investigations. The system which resulted from several years of development and use in a number of field investigations is described below. It has become known as PANDORA (Programmable Automatic Noise Data and Other Related Paramater Acquisition system).

2.   FUNCTIONAL CAPABILITY

In general terms, the function of the measurement system is the unattended collection of noise level data (and other related parameters) in digital and analogue form. Additionally, the system can be programmed to operate during preferred times or when certain conditions prevail.

General views of the microprocessor console are shown in Fig.1 and a simplified schematic diagram of the system is shown in Figure 2. This illustrates that upto eight analogue input signals can be accepted which, after signal conditioning, are available for analogue recording systems (tape or chart recorders). These recording systems can either be operated continuously or in a sampling mode under the control of a central processing unit (CPU). Following further signal conditioning (to provide a standard 0-100mV DC input signal range), the signals are fed to a scanning unit and analogue/digital converter. For each sample initiated, the CPU produces serial ASCII pulse coded signals indicating the input

levels for each of the eight channels, plus date and time information with a "reason for sample" prefix. The digital data is further processed to provide a range of output formats for storage on FM and/or DR tape recorders and direct teletype drive.

Sampling rates and durations are determined by a set of thumbwheel switches which also permit the selection of pre-programmed operational modes and the setting of threshold operating levels. Provision is also made for remote control of sample initiation. Integral with the microprocessor unit are a NIXIE LED display and keyboard to provide indications of channel signal levels, time and date, control switch settings and also to initiate manual samples and the injection of calibration signals.

The stored analogue and digital data - usually on a twin track stereo recorder - is analysed subsequently in the laboratory. The digital data is fed directly to a computer (PDP11/34) or desk top calculator (HP 9825A) to carry out statistical analyses, whilst the corresponding analogue signals are available for a range of time/frequency domain analysis methods.

This system, which has evolved out of a range of noise investigations over a number of years, is currently in use at three locations and examples of its application are given in Sections 4 and 5. Whilst the authors' experience is limited to the application of this method to acoustic investigations it can, obviously, also be employed in other investigations of dynamic phenomena where sampling techniques are applicable.

3.   OPERATIONAL DETAILS

   3.1   Input Signal Conditioning

      The system is designed to accept two plug-in cards in series per channel. The first card is to provide impedance matching, amplification, filtering etc. as desired and the second to convert the required signal measurement range to the 0-100mV DC standard input required for the A/D converter.

      To date, the following cards have been designed, constructed and used in investigations:-

      (a)   Acoustic Signals (from B & K Outdoor Sound Level Meter)

             'A' Weighting, 100Hz 1/3 octave, 8kHz 1/1 octave filters

      (b)   Other parameters:

             Wind speed and direction (from local temporary installations and/or permanent meteorological instruments)

             Humidity

             Machine load (kW)

Machine RPM

Yaw error angle

Further details are given in the examples quoted in Sections 4 and 5.

3.2 The Microprocessor Unit - based on Intel SDK-85 Kit

3.2.1 Timing Controls

A crystal controlled clock provides the basic reference for time and date information, sampling frequency and sample length. In addition, it provides a stable 12kHz frequency carrier for the direct record ASCII coded digital data output. To overcome the problem of time and date resetting to zero following a mains supply interruption, a "floating" battery supply has been provided to ensure continuity of time and date information, even though data gathering is not possible during the period when the mains supply is off. The battery supply can maintain the timing circuits for a period of up to 3 hours.

BCD thumbwheel switches are used to set sample intervals over the range 0-99 minutes and sample durations of 0-99 seconds for normal sequential sampling. For out of sequence timing, using the "threshold exceeded" facility (see Section 3.2.2), further thumbwheel switches are used to set alternative sample intervals in the range 1-18 minutes for Modes 1-5 but the range is extended to 90 minute intervals in Mode 6 (see Section 3.2.2). For example "normal" sampling could be set to one 10 second sample every hour to obtain background noise data and if a pre-selected noise threshold of 60dB(A) had been selected and exceeded, the sample frequency would be increased to provide one 10 second sample every minute. Further examples are provided in Sections 4 and 5.

Every time a sample is taken, for whatever reason, a start/stop signal is available to control external recorders. The digital data train for each sample is also preceeded by a "reason for sample" code, thereby identifying it uniquely (see Table 1).

3.2.2 Threshold Control of Sampling Rate

As stated earlier, it is frequently useful to concentrate data collection when certain conditions prevail. This can be achieved by means of a threshold sensing technique which permits variation of sampling rate according to the input level on any one or two of the eight input channels.

This equipment provides a range of operational modes (1-6) to cater for a variety of noise investigations. These modes are listed in Table 2 together with details of sample initiation options and coded print-out prefixes. There is sufficient memory to provide for four additional modes to be programmed in, if required.

Selection of the parameters controlling threshold operation
is by means of thumbwheel switches as follows:-

(a)   Mode Number (1-6)
(b)   Channel(s) controlling sample rate
(c)   Threshold levels on selected channels
(d)   Time delay (threshold to be exceeded for 0-99 seconds
       before sample rate changed)
(e)   Sample rate above and below threshold level

3.2.3 Nixie Display and Keyboard

The microprocessor contains a 24 point keyboard and digital
LED display and the following parameters can be selected and
displayed:-

Time - normal display, returns to this after 90 secs. on any
       other setting
Date
Input levels, channels 1 - 8
Settings of sample interval, threshold level and mode
switches

The keyboard is used to set time and date (Test C) and also
to obtain manual samples. An additional feature (Test 9)
initiates the following start-up sequence:-

Calibration signals applied to appropriate channel inputs
and 30 second analogue recordings available. During this
period, digital data is provided to indicate switch settings
(Prefix I) followed by a further train of digital data of
calibration figures for channels 1 - 8 (Prefix S).

This sequence is also initiated when the automatic daily
calibration (at 1205) occurs but with prefix C instead of
I and S.

4.   DATA STORAGE AND COLLECTION

Due to the flexibility designed into this measuring system there are a
large number of options available for data recording. The simplest format
used to date (to determine background noise levels) utilises a commercial
stereo cassette recorder where one channel stores an analogue sample
recording of the wide-band acoustic signal whilst the other channel is
fed with digital data in ASCII code (via a 12kHz carrier signal)
containing date, time, dB(A) SPL, wind speed and wind direction related
to the analogue sample. Recently, this system has been extended to permit
two analogue signals to be recorded, one on each channel, with the digital
data superimposed on one analogue recording using the 12kHz carrier which
is outside the audio frequency range of interest.

Investigations requiring data on many parameters have employed a 4 channel FM recorder, stereo cassette recorder and paper chart recorders. In this case (the measurement of noise from aerogenerators) the arrangement is as follows:-

FM Recorder

Channel 1 Infrasonic signal ($\leqslant$100Hz) from Microphone 1
Channel 2 Infrasonic signal ($\leqslant$100Hz) from Microphone 2
Channel 3 Instantaneous (low damping) local wind speed signal
Channel 4 DC ASCII data

Cassette Recorder

Channel 1 Audio signal (40Hz - 10kHz) from Microphone 3
Channel 2 Audio signal (40Hz - 10kHz) from Microphone 4
          plus ASCII data on 12kHz carrier

Paper Chart Recorder (Continuous Running)

Channel 1 Wind speed (high damping) - local)
Channel 2 Wind direction - local

The ASCII coded data consists of:-

DATE
TIME
1.   dB(A) slow
2.   Wind speed - local
3.   Wind direction
4.   Machine load
5.   Rotor RPM
6.   Yaw angle
7.   Wind speed
8.   Wind direction

In this manner, a range of parameters can be measured in analogue sample format or as single digital readings which can be synchronised in time. Obviously, as the investigation progresses the most significant parameters can be recorded as analogue signals for more detailed analysis.

The two examples quoted above demonstrate the capability of the system in terms of the range of parameters measurable and the flexibility of operation is considered in the following section.

5.   OPERATION OF THE SYSTEM IN FIELD STUDIES

   5.1   Background Noise Surveys - New Sites

      Here the requirement is to establish the minimum background noise levels in the area, which usually occur in the early morning hours at low wind speeds. Consequently, after some initial trials, the measurement system was set up as follows:-

Equipment   B & K Outdoor Sound Level Meter (Type 4921)
             Evershed and Vignoles Wind Speed and Direction
              indicator (Type WD200-SD)
             Microprocessor controller
             Nakamichi Sterio Cassette Recorder (Type LX3)
              Channel 1 Analogue audio signal (40-10000Hz)
              Channel 2 ASCII coded data comprising:-
                     Time
                     Date
                     dB(A)
                     Wind speed
                     Wind direction

Sample Timing and Threshold Settings Selected

             Mode 6
             Channel to operate threshold (wind speed)
             Threshold level at 3m/sec
             Sample duration at 10 sec
             Delay time for threshold operation 30 secs
             Sample interval below threshold 10 minutes
             Sample interval above threshold 60 minutes

This method of operation concentrated data collection during low
wind speed conditions whilst still obtaining data sufficient to
calculate the effect of higher wind speeds on background noise and
the percentage of time that the low background noise conditions
prevail by subsequent analysis. Mode 6 was, in fact, developed to
provide for a lower sampling rate above threshold as this had not
been anticipated before this application of the system was
required.

5.2   Aerogenerator Noise Emission and Background Noise at High Wind
      Speeds

This investigation is different to most other noise problems since
it requires the acquisition of data over the aerogenerator operating
wind speed range (3.5 - 13m/sec). Usually, one is concerned with
obtaining noise measurements with low background noise i.e low wind
speeds.

Originally, a measurement system was installed adjacent to the
nearest residences but recently an additional system has been
devised and installed to obtain noise emission and background noise
data in the "near field", approx. 50m from the aerogenerator. This
system is comprised of:

      Four outdoor microphone units (2 sonic + 2 infrasonic)
      A 4 channel FM tape recorder
      A stereo cassette recorder
      Wind speed and direction sensors local to the microphones
      Signals (e.g load, rpm etc) from sensors forming part of the
       aerogenerator control system

The details of the recording system and range of parameters covered
are given in Section 4.

Sampling Timing and Threshold Settings

> Mode 2
> Channel to control sample rate (wind speed)
> Threshold 1 level at 5m/sec
> Sample duration at 30 sec
> Sample interval below threshold 60 minutes
> Sample interval above threshold 10 minutes
> Delay time for threshold operation 30 secs

The data obtained from the system has provided sufficient data to
establish the relationship (in statistical terms) between background
noise (dB(A) and octave band SPL's) and wind speed. It will also
permit the correlation between machine parameters (load, yaw angle
etc) and noise emission levels to be investigated when the
aerogenerator is fully commissioned.

6. DATA ANALYSIS

As indicated earlier, the inherent flexibility of the data recording
system permits the use of a wide range of analysis methods. Obviously,
in a particular investigation the overall measurement/analysis system
must be considered as a whole so as to concentrate data collection during
relevant periods and thereby minimise analysis effort. To date, the main
investigations employing this system have required statistical analyses
of noise data and the relationships between noise level and wind speed
as described below.

6.1 Analysis of Digital Data

The ASCII coded data is available for immediate printout on a
teletype but, more usually, is stored on either a FM or DR tape
recorder. For DR recordings, using a 12kHz carrier, a decoder is
available to convert the coded signal for subsequent presentation
to a teletype, computer or desk top calculator in either RS232 or
20mA loop format.

Programs have been written for the PDP11/34 computer to collect,
clasify and file the digital data and to calculate simple
statistical parameters (mean, SD, percentiles etc). The following
examples will serve to illustrate:-

(a) Background Noise - New Sites

The system described in Section 5.1 has been used to collect
around 8,000 samples mainly at low wind speeds (3m/sec)
during the first 9 months of the survey. These have been
analysed to provide the background noise level statistics in
dB(A) terms as illustrated in Table 2. In this case, the major
interest is in describing the lowest existing noise climate
and a range of statistical parameters have been obtained to
permit the most appropriate description to be chosen.
Basically, the noise data has been classified in terms of wind
speed bands of 1m/sec and eight wind direction sectors. The
mean, SD and L_{95} ---- L_{05} percentiles have been

calculated for each class in addition to "total sample" figures.

(b)   Aerogenerator Noise

As opposed to the example quoted above, it is necessary to characterise both the background noise and aerogenerator noise emissions over the operating wind speed range (3.5 - 15m/sec). Using the same program, the collected data is classified into wind speed bands 1m/sec wide and the statistical parameters displayed as shown in Fig.3. To date, no significant data on noise emissions have been obtained due to machine operating problems but provision has been made for alternative data classification in terms of machine electrical load, yaw error angle etc. to determine the relationships between noise level and the various operating conditions.

The general program has been written so as to provide for considerable flexibility in the treatment of sampled data. Once the data has been filed, it can be classified in a variety of ways (e.g according to time, date, wind speed and direction etc) within variable limits which can be selected during the setting-up procedure.

6.2   Analogue Data Analysis

6.2.1 Audio Check

The simplest (and often most useful) method is to listen to the tape when replayed at periods of interest or when there may be apparently anomalous digital data results. Putting a pair of ears into the measurement situation can often resolve many problems!

6.2.2 Spectrum Analysis

For more detailed spectrum analysis and/or the provision of a permanent record, a real time 1/1, 1/3 octave or 400 line FFT analysis can readily be obtained. In SWR SSD, B & K Type 2131 and Nicolet analysers are employed to obtain this data by manual operation on samples of interest.

Progress is also being made in a scheme to automate the spectrum analysis so that this data can be subjected to the same statistical analysis as that already available for the dB(A) level in the digital data train. The method involves the use of a B & K Type Real Time Analyser and Digital Tape Recorder controlled via the IEEE interface bus by a HP 9285A Desk Top Calculator. The system has been demonstrated to work in principle using a part-automatic, part-manual method of operation. Suitable interface cards can be obtained for the HP calculator to fully automate the process.

6.3　Time Domain Analysis

Stored analogue data can also be subjected to analysis by
correlation and/or coherence function analysis to provide
information on source identification, transmission path
characteristics etc.　To date, these techniques have not been
employed in field investigations but when regular operation of the
prototype aerogenerator at Carmarthen Bay is achieved, they will
be applied to the problems of characterising noise emissions.

7.　POSSIBLE FUTURE COMMERCIAL EXPLOITATION OF THE SYSTEM

From the two original laboratory built prototypes a specification and
a set of working drawings were obtained and a number of commercially
constructed equipments have been produced by Hereford Microsystems
Limited, under licence.　Two have been purchased by SWR SSD, one each
by NSHEB and SER SSD.　Following the circulation of this report, it is
intended to hold a short seminar to demonstrate and discuss the
performance and application of this equipment with interested Board
Departments.　Depending upon the response to this seminar and future
demand, licensing arrangements will be reviewed.

8.　CONCLUSIONS

8.1　The PANDORA system described in this report provides a versatile
method of investigating a wide range of noise problems with the
following advantages over conventional methods:-

(i) savings of skilled manpower time on site

(ii) data collection in both digital and analogue form permits
a variety of analytical techniques to be applied (statistical,
time and frequency domain)

(iii) programmable data collection minimises subsequent analysis
effort

8.2　Field investigations currently in progress have demonstrated the
suitability and effectiveness of the equipment.

9.　REFERENCES

1.　"A Prototype Long-term Noise Monitoring System Using Time-Sampling
Techniques" by M R Burt, SSD/SW/78/N5.

2.　"A Long-term Noise Monitoring System: Recent Developments and
Equipment Reliability" by M R Burt, SSD/SW/79/N147.

3.　"Noise Monitoring on Pembroke P.S Boundary Using a Microprocessor
Controlled Noise Monitor" by M R Burt, SSD/SW/81/M18341

4.　"A Prototype Microprocessor Controlled Time-Sampling Noise Measuring
System" by M R Burt, SSD/SW/81/N6.

DYN01PNDM0AP

TABLE 1
THRESHOLD OPERATION MODE OPTIONS

MODE NO	SAMPLE INITIATION	DIGITAL PRINTOUT PREFIX	OPERATION
1	Remote Control Manual Sample Normal Timed Sample Daily Automatic Calibration (1205hrs)	R M T C	No threshold operation available
2	Remote Control Manual Sample Normal Timed Sample Daily Calibration Threshold 1 'High' Above Threshold Timed Sample Threshold 1 'Low'	R M TL C H1 TH L1	Threshold control on any one channel When exceeded, sample is taken (H1) and subsequent samples (TH) are at a higher rate. When signal falls below threshold, sample is taken (L1) and subsequent samples (TL) are at the normal rate
3	Threshold 1 'High' Threshold 2 'High' Threshold 1 'Low' Threshold 2 'High'	H1 H2 L1 L1	Threshold control on any two channels. Samples only initiated at the time each channel goes 'high' or 'low'
4	Remote Control Manual Sample Normal Timed Sample Daily Calibration Threshold 1 'High' Threshold 2 'High' Above Threshold Timed Sample Threshold 1 'Low' Threshold 2 'Low'	R M TL C H1 H2 TH L1 L2	Threshold control on any two channels. Sample rate increases when either channel goes 'high' and returns to normal rate only when both channels go 'low'
5	Remote Control Manual Sample Normal Timed Sample Daily Calibration Threshold 1 'High' Threshold 2 'High' Above Threshold Timed Sample Threshold 1 'Low' Threshold 2 'Low'	R M TL C H1 H2 TH L1 L2	Threshold control on any two samples Requires both channels to go 'high' to increase sampling rate. If one channel goes 'low' a sample is taken but sampling rate remains high. When both channels go 'low' system reverts to normal sampling rate.
6	Remote Control Manual Sample Normal Timed Sample Daily Calibration Threshold 1 'High' Threshold 2 'High' Above Threshold Timed Sample Threshold 1 'Low' Threshold 2 'Low'	R M TL C H1 H2 TH L1 L2	Threshold control on any two channels. Similar to Mode 4 but sampling rate when both thresholds are 'high' can be selected to be slower than normal sampling rate. [A factor of 10 is applied to the "Above Threshold Sample Interval" switch indication (8L)]

TABLE 2

SITE NOISE SURVEY - LOW WIND SPEED DATA SUMMARY
MONTHS JUNE, JULY AND AUGUST

WIND SPEED M/SEC	WIND DIRECTION	NO. OF SAMPLES	MEAN db(A)	S.D.	L95	L90	dB(A) L50	L10	L5
0 - 3	NE	110	34.9	5.1	26.3	28.7	34.8	41.0	44.8
0 - 3	E	86	34.5	4.8	25.8	27.1	34.5	39.8	41.4
0 - 3	SE	11	34.0	5.9	24.5	25.1	32.5	40.9	41.5
0 - 3	S	35	34.1	6.9	24.9	26.2	32.8	42.8	45.6
0 - 3	SW	49	33.8	5.7	25.5	27.5	32.5	39.1	43.6
0 - 3	W	277	-3.8	6.5	25.3	26.5	32.8	42.4	45.6
0 - 3	NW	105	33.0	5.0	25.3	26.5	31.9	40.2	41.7
0 - 3	N	76	34.6	5.7	26.3	27.8	33.8	41.4	45.2
0 - 3	All Directions	749	34.0	5.8	25.5	26.8	33.4	41.1	44.1

2200 HOURS - 0700 HOURS

WIND SPEED M/SEC	WIND DIRECTION	NO. OF SAMPLES	MEAN db(A)	S.D.	L95	L90	dB(A) L50	L10	L5
0 - 3	NE	216	39.8	4.7	33.5	34.3	39.1	44.9	47.3
0 - 3	E	58	40.9	4.3	33.9	34.7	40.5	45.1	46.4
0 - 3	SE	11	44.9	5.2	37.5	38.1	43.5	48.9	56.5
0 - 3	S	10	43.3	8.9	34.5	35.0	42.0	47.0	66.5
0 - 3	SW	18	38.9	8.0	26.9	28.8	38.0	53.1	53.5
0 - 3	W	285	40.6	5.5	32.1	34.4	40.0	47.1	49.9
0 - 3	NW	218	40.6	5.4	32.2	33.7	39.7	47.3	48.9
0 - 3	N	190	40.3	5.2	32.8	34.2	39.3	46.2	49.5
0 - 3	All Directions	1006	40.4	5.3	32.8	34.2	39.7	46.5	48.9

0700 HOURS - 2200 HOURS

BACKGROUND NOISE LEVEL STATISTICAL ANALYSIS
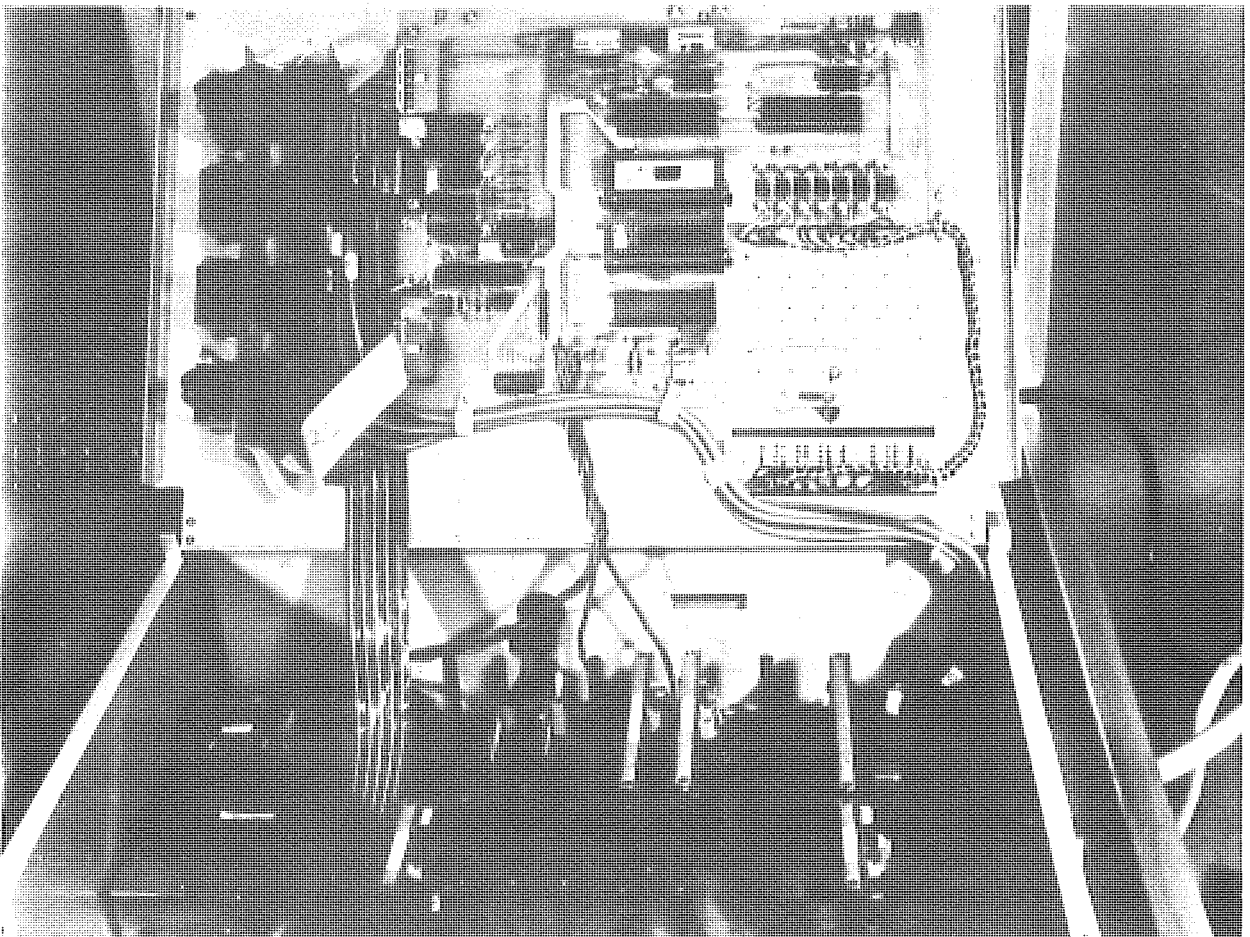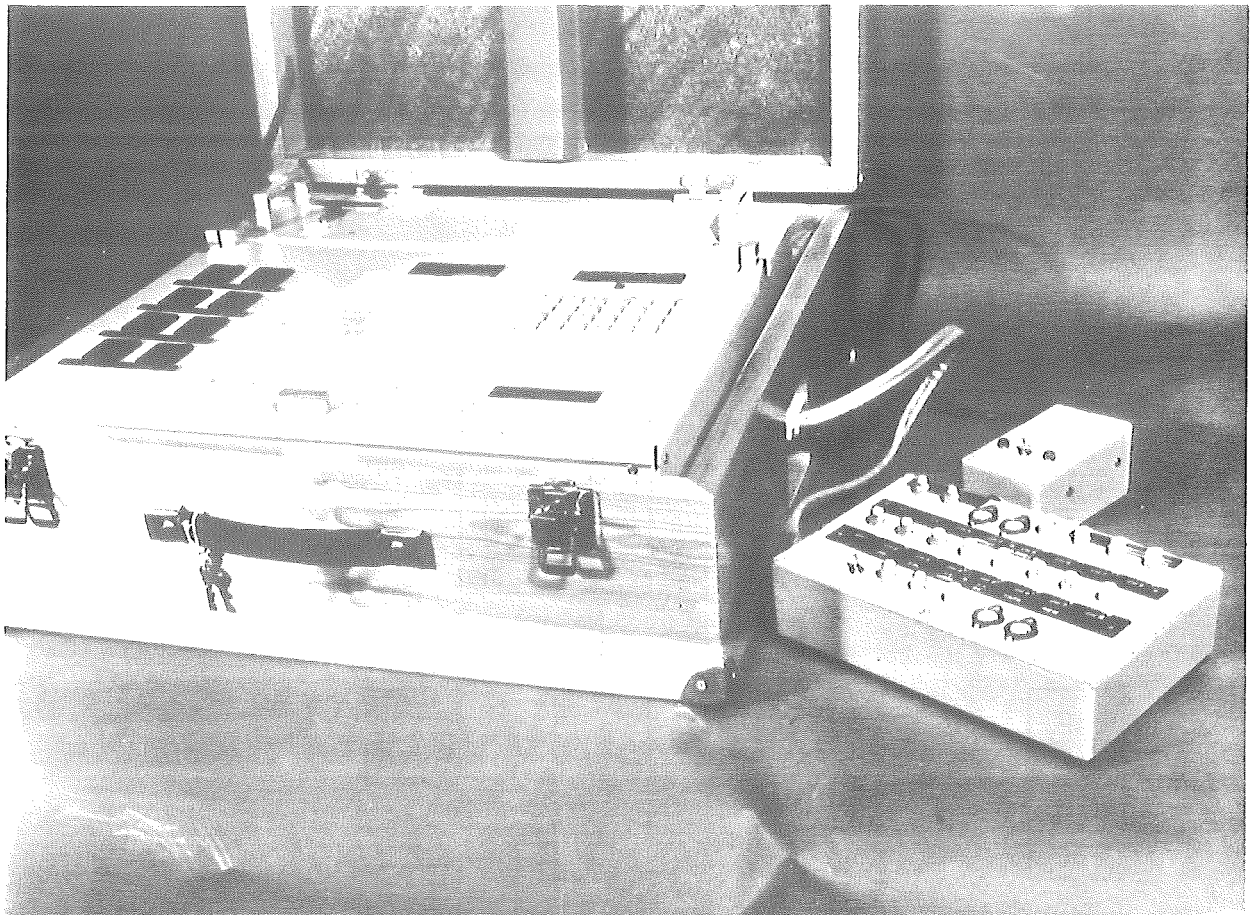
Fig.1. External and internal views of the console.
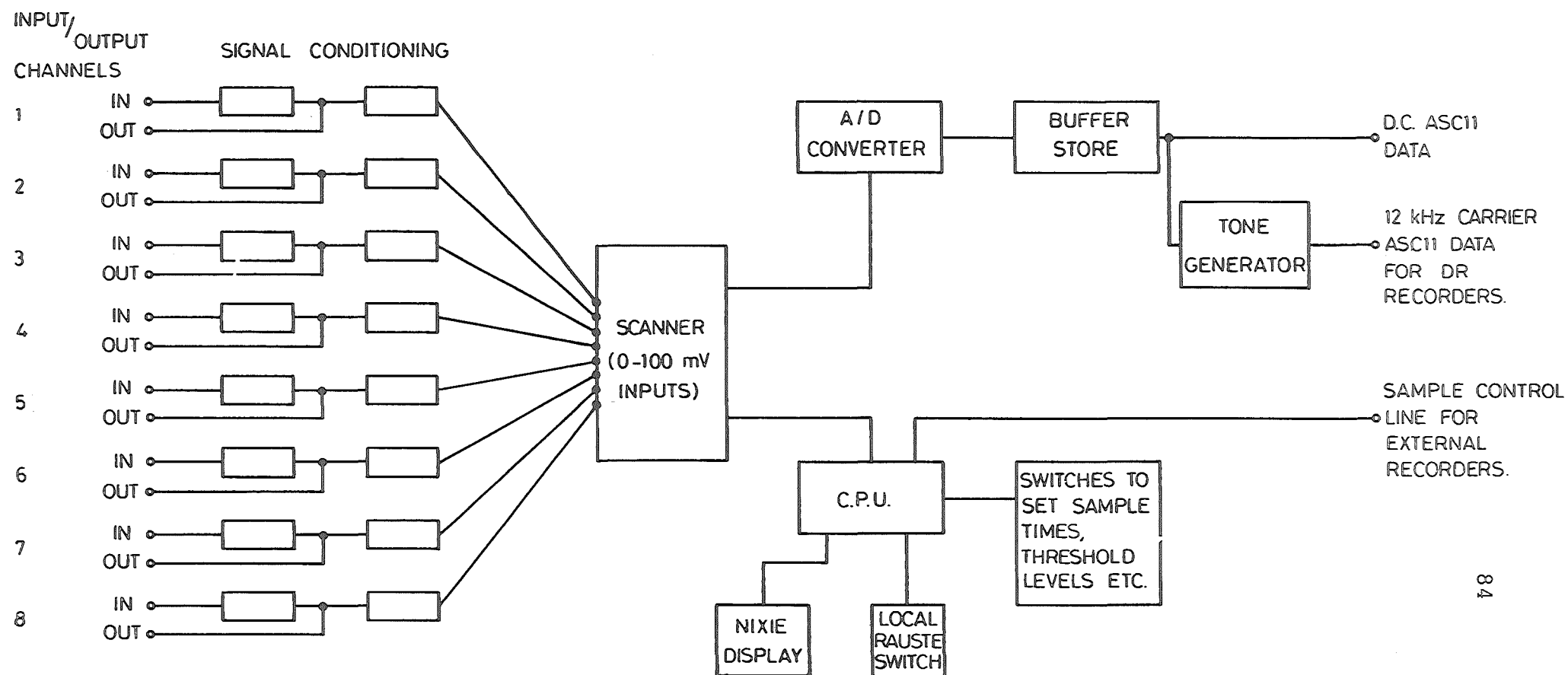
FIG. 2. SCHEMATIC DIAGRAM OF MEASUREMENT SYSTEM
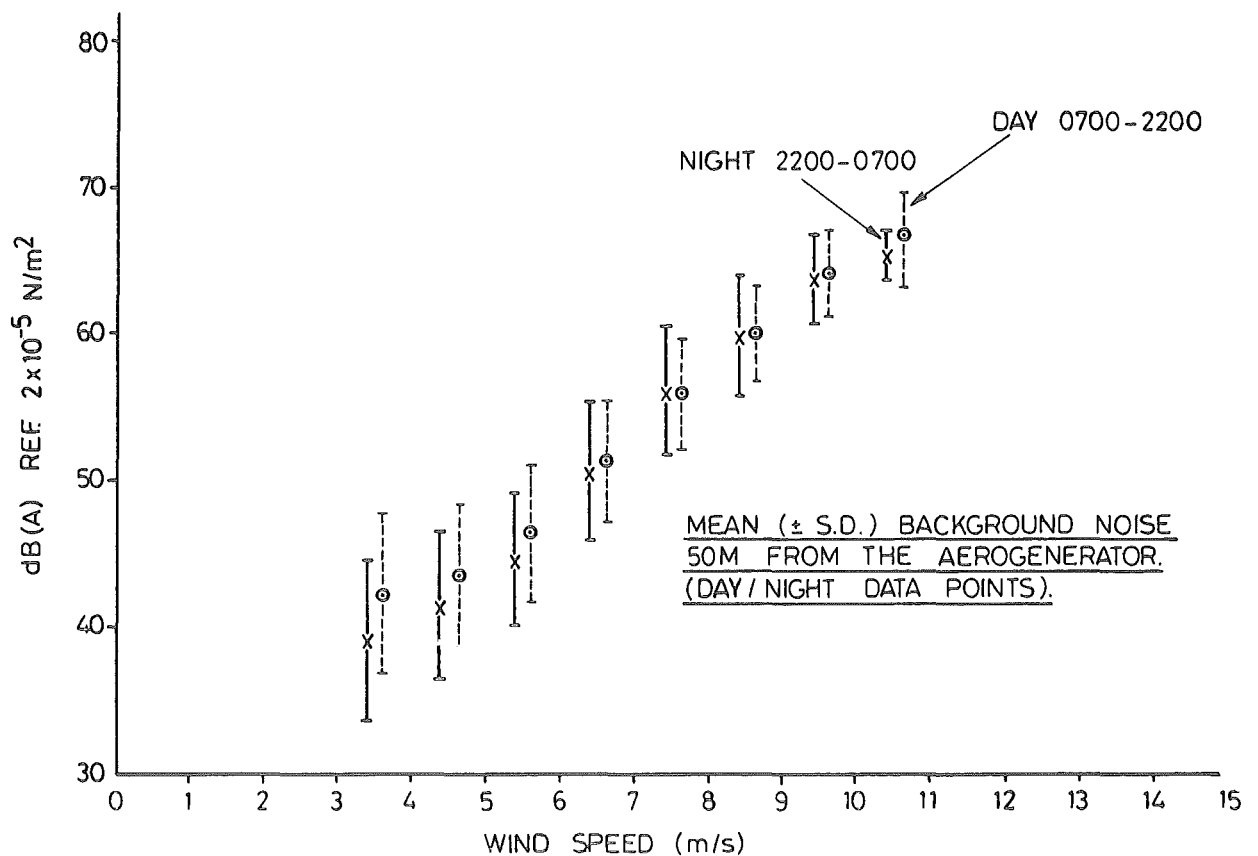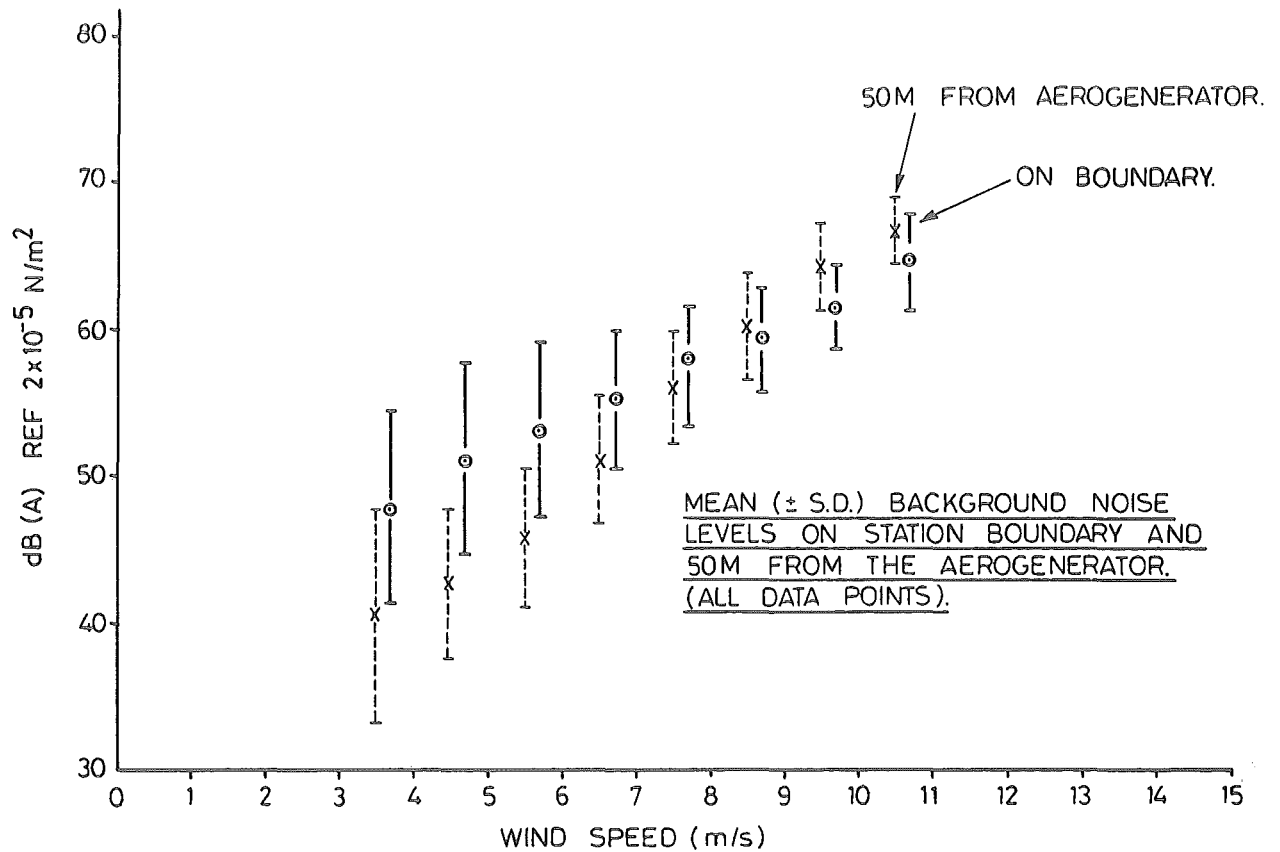
FIG. 3. BACKGROUND NOISE Vs WIND SPEED.

TV-interference at the Maglarp Wind Turbine

Mats Agrell, SYDKRAFT
Ulf Teght, TELEVERKET

Summary

1. The TV-interference from the wind turbine at
   Maglarp is severe when the unit is running.

2. The disturbed area is mainly behind the wind
   turbine seen from the transmitter but TV-inter-
   ference is reported outside this area at some
   wind-directions.

3. The TV-interference is probably caused by the
   lightning protection tape on the blades. The tape
   protects the cables to the strain gauges and is
   oriented as a grid.

4. TV-interference problems can be solved by instal-
   ling a TV-transmitter close to the wind turbine at
   a place where the transmitter can recieve an
   undisturbed signal.

Introduction

This report is the result of the measurments made by the Swedish State Telecommunication Board on the TV-interference at the Maglarp wind turbine. The report gives also some basic information on TV-broadcasting in Sweden and how the interference problem at Maglarp is solved today.

TV-broadcasting in Sweden

Sweden has two TV-channels that broadcasts non-comercial programmes in general from 6 p.m. to 11 p.m.

During weekdays school-TV broadcasts programmes three days a week on one channel and during week-ends there are TV also on day-time (Sports, re-runs, movies etc).

Channel one, called TV1, is transmitted both on the VHF and UHF band. Channel two (TV2) is always transmitted on the UHF band. In the area where Maglarp is situated the Hörby TV-transmitter is normally used. The distance to the transmitter is 65 km.

Hörby has the following data:

Name	Band	Cannel	P kW
Hörby TV1	UHF	43	1000
Hörby TV2	UHF	33	1000

People in the south of Sweden also watch the Danish TV programmes.
Danmark has only one TV-cannel transmitted on the VHF band.

Cable-TV is under test-operation in some cities in Sweden. The cable-TV network is used for either transmitting local commercial programmes or re-transmitting TV from other contries.

Satellite-TV is yet in very little use in Sweden, though it is possible to pick-up signals intended for Russia, Argentina and other exotic countries.

For the next few years the people in Sweden will be using TV-signals broadcasted through the air as at Maglarp today. The problem with TV-interference from a wind turbine has to be taken in consideration when planning for a new wind turbine site.

Complains on the TV-interference

Shortly after the first test-runs of the Maglarp wind turbine complains came in, from people living in the neighbourhood, on TV-interference. The interferences are severe only when the wind turbine is running and two areas can be identified:

1. The village Skåre situated 2 km from the turbine and on a direct line from the transmitter at Hörby - through the tower of the turbine - and to the center of the village. See figure 9 on page 10. Some of the houses in the village have severe TV-interference all the time the rotorblades are rotating. The interference from the tower can be observed in a few houses.

2. Some of the houses in the area have on some occasions TV-interferences depending on the direction of the nacelle and only when the rotor blades are rotating.
   These TV-interferences are observed on the VHF-band (Denmark) and on the UHF-band.

TV-interference measurments

Measurments were carried out in October 1983 by the Swedish State Telecommunication Board. The report by Ulf Tegth and Lennart Sundberg in reference 1 is in Swedish but the main results are given below.

Basic studies

TV interference was measured at the Swedish test wind turbine at Kalkugnen in 1979 (Ref. 2). A prediction was made of the TV-interference from a wind turbine of Maglarps size.

The main effect of TV-interference from a wind
turbine can be explained from Figure 1.
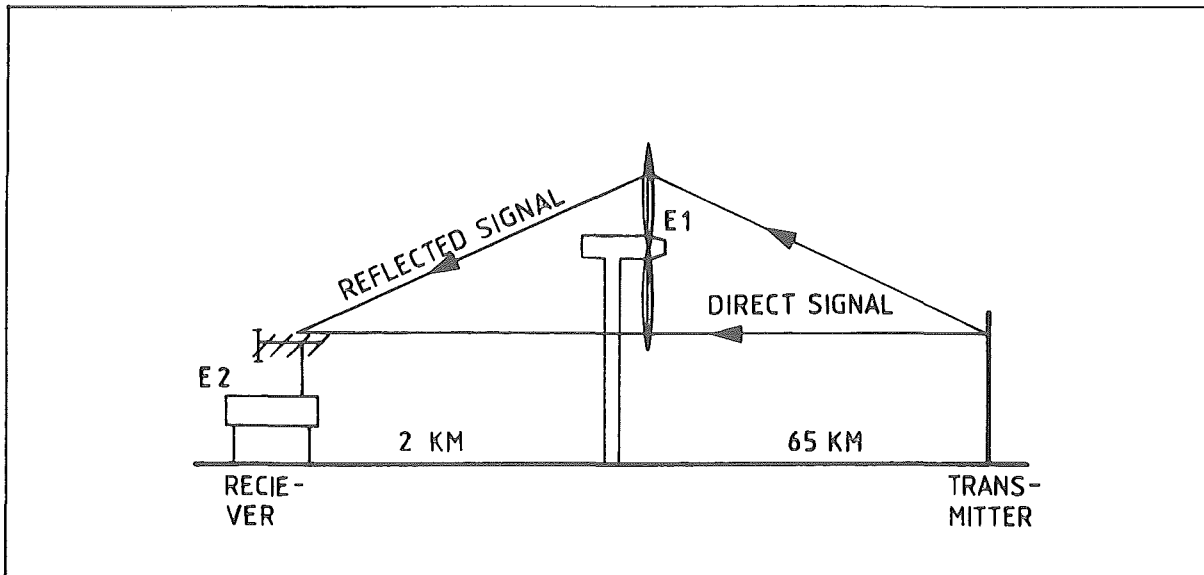
Figure 1   Direct and reflected TV-signal
                  is recieved by the TV-set.

                  TV-signal at E1:   98 dBuV/m, UHF channel 33
                  TV-signal at E2:   80 dBuV/m, UHF channel 33

The TV-signal goes two ways:
The direct signal from transmitter to reciever and
the signal that is reflected on the aluminum tape
on the blades and thus has a longer way to go be-
fore it reaches the reciever antenna.

The reflected signal is slightly delayed and can be
observed as a "shadow" on the right of a vertical
line in the TV-picture if the difference in distance
between the direct and reflected signal is over
approx. 30 m.

The reflected signal can be of a higher signal
strength than the direct signal because the TV-sig-
nal at hub height (75 m) at Maglarp is considerably
higher than the signal at the the level where the
houses have their TV-antennas.
The difference in signals in the measured area is
between 15 and 25 dB.

Disturbed area

The measured area with interference forward from
the transmitter was both on a greater distance from
the turbine and in a larger sector compared with
the predictions. The backward area, towards the
transmitter, was smaller than predicted.
The predictions was however made on blades made of
reinforced fibre glass with only aluminum tape at
leading and trailing edge.

The blades have aluminum tape for lightning protec-
tion layed out as a grid as can be seen in figure 2
on the next page.

Blade positions

TV-interference was observed with the blades both
in horisontal and vertikal position:

Horisontal blades

A schematic wiew of the interference is shown in
figure 3.
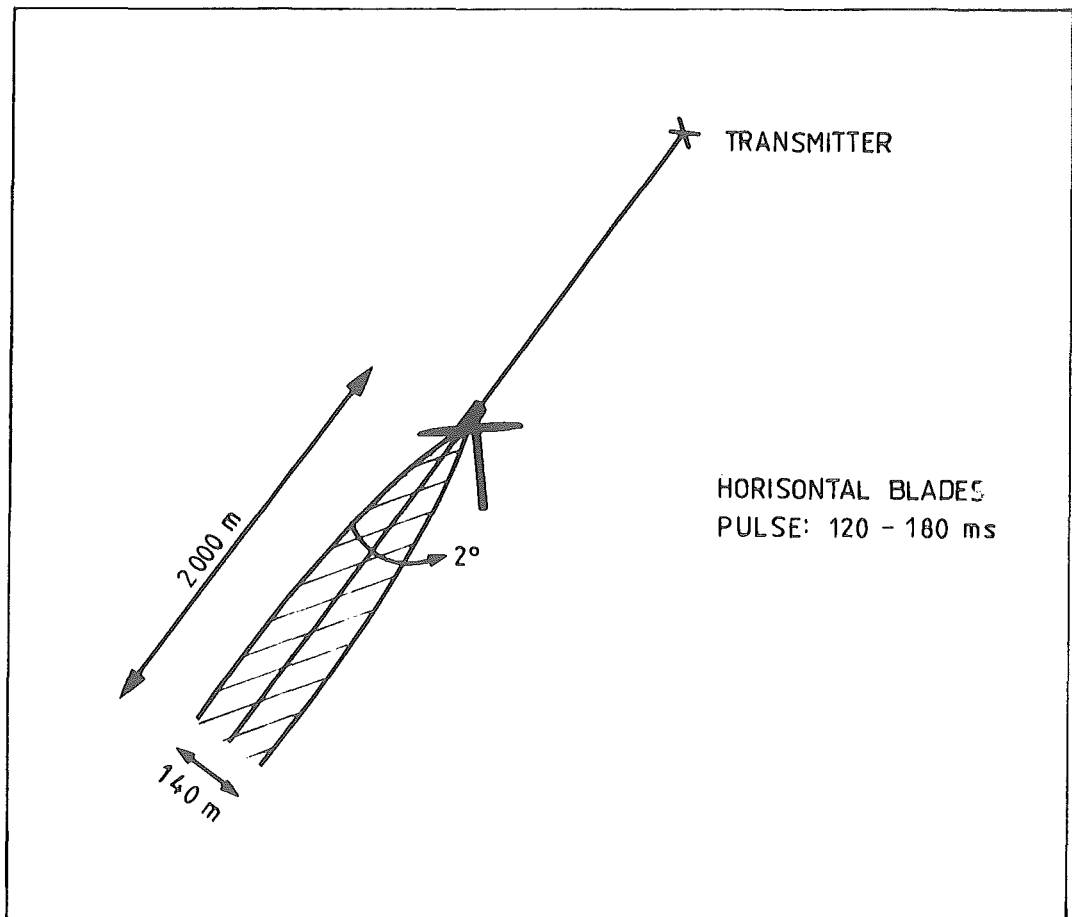
Figure 3   Horisontal blades - narrow area
                      and long pulses
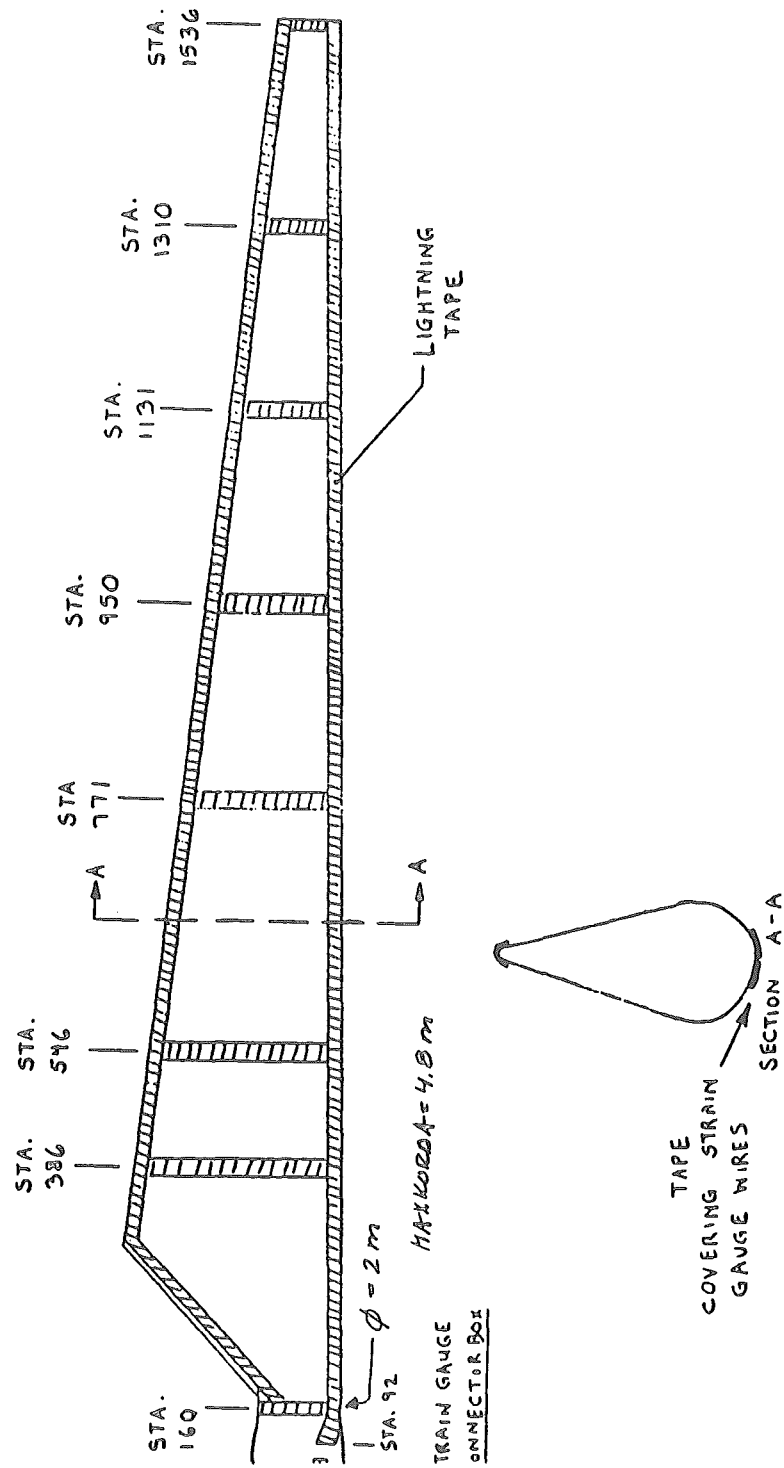
Figure 2   Lightning protection tape on blade

The disturbed area is within a narrow sector of approx. 2 degrees.
The duration of the pulse is long: 120 - 180 ms.

Vertical blades

Interference from vertical blades give a disturbed area of parabolic type. The duration of the pulse is short: 40 ms. This type of interference was dominating in the village Skåre. A schematic wiew is shown in figure 4.
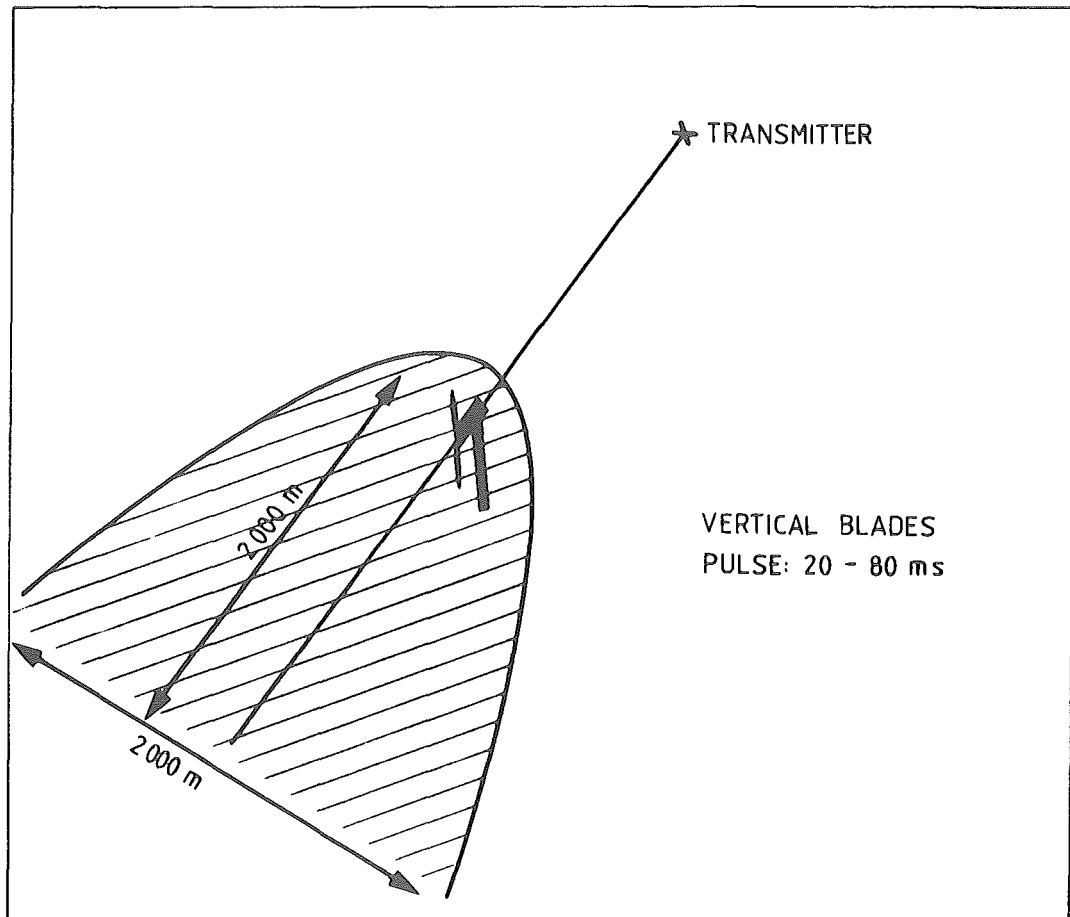
Figure 4   Vertical blades - parabolic area and short pulses

Effects on the TV-picture

The signal for the TV-picture is amplitude modula-
ted (AM). It is thus sensitive to disturbances of
the amplitude of the signal - the signal strength.

The signal for TV and radio-sound is frequency
modulated (FM) and the reciever can depress the
variations in signal strengh.

The FM signal is sensitive to differences in time
between a direct and reflected signal but there are
no complains on Radio- or TV-sound at Maglarp yet.

A TV reciever is equipped with an Automatic Gain
Control (AGC) that can compensate for variations in
the signal strength.
The response time of the AGC is typically 120 ms.

Figure 5   Pulses with long duration, as in the case with
                     horisontal blades, is well compensated by the AGC.

Figure 6   Short pulses, as with vertical blades, can not been
                     taken care of by the AGC.
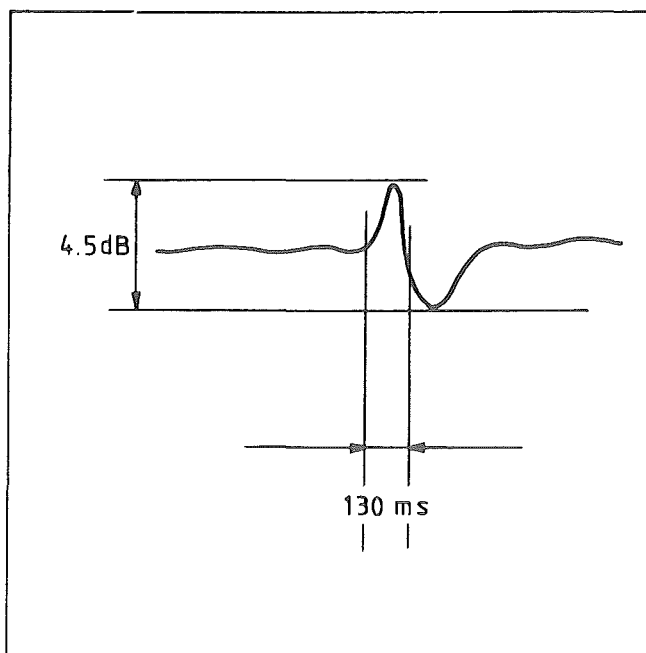
Figure 5
Long duration pulse
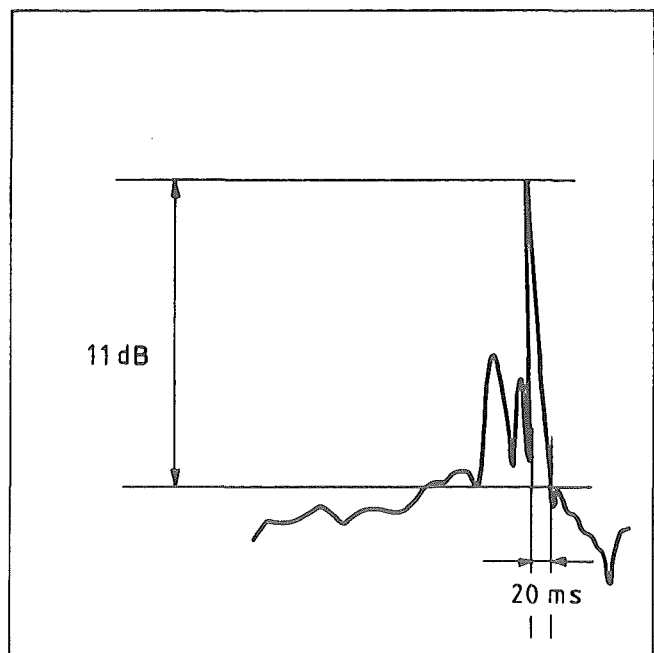
Figure 6
Short duration pulse

The interference is both of a positive (higher signal strenth) and a negative (lower signal strength) shape.

Figure 7   The positive pulse disturbes the syncronisation of the picture - it jumps.

Figure 8   The negative pulse gives noise in the picture - it looks like "snow".
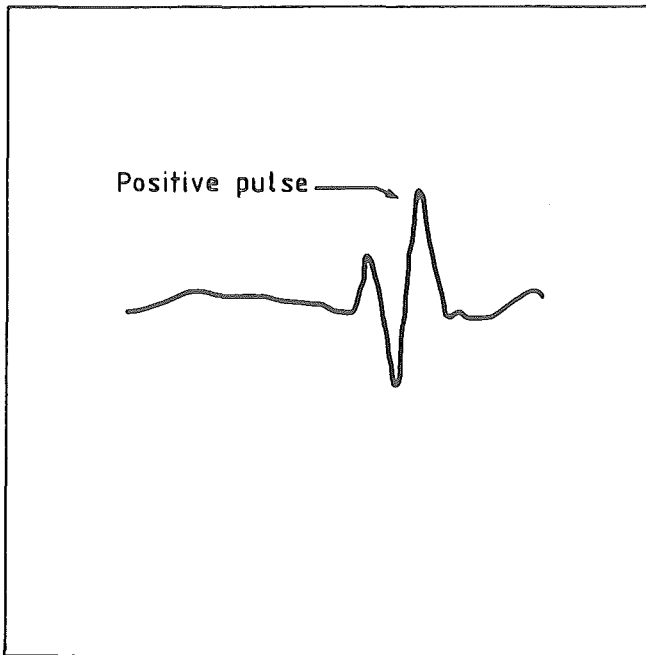
Figure 7

Positive pulse - disturbed
syncronisation
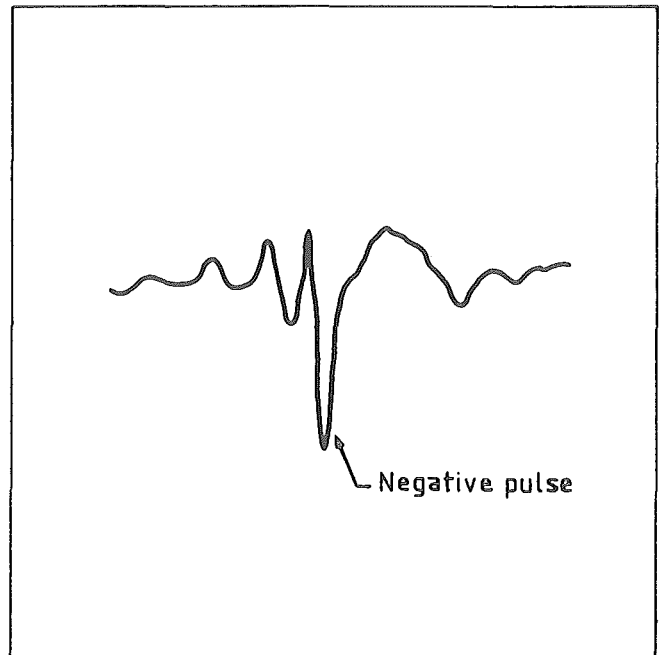
Figure 8

Negative pulse - noise

Slave-transmitter installation

Shortly after the measurments were completed the work on a possible solution started. In December 1983 a slave-transmitter was installed on the meteorological tower 200 m west of the turbine.

The electronic equipment for reciever and transmitter was installed in a little house, intended for the microcomputer to the meteorological measurments, close to the mast.

The transmitter has the power of only 2 W and a covered area of 60-90 degrees up to a distance of 5 km. Se figure 9.

The channels are transmitted on UHF channel 38 for TV1 and on UHF channel 44 for TV2.

METEOROLOGICAL TOWER
WITH SLAVE-TRANSMITTER
P = 2 (WATT)

AREA WITH TV-INTERFERENCE

TO HÖRBY
TV-TRANSMITTER
UHF Ch. 33,43
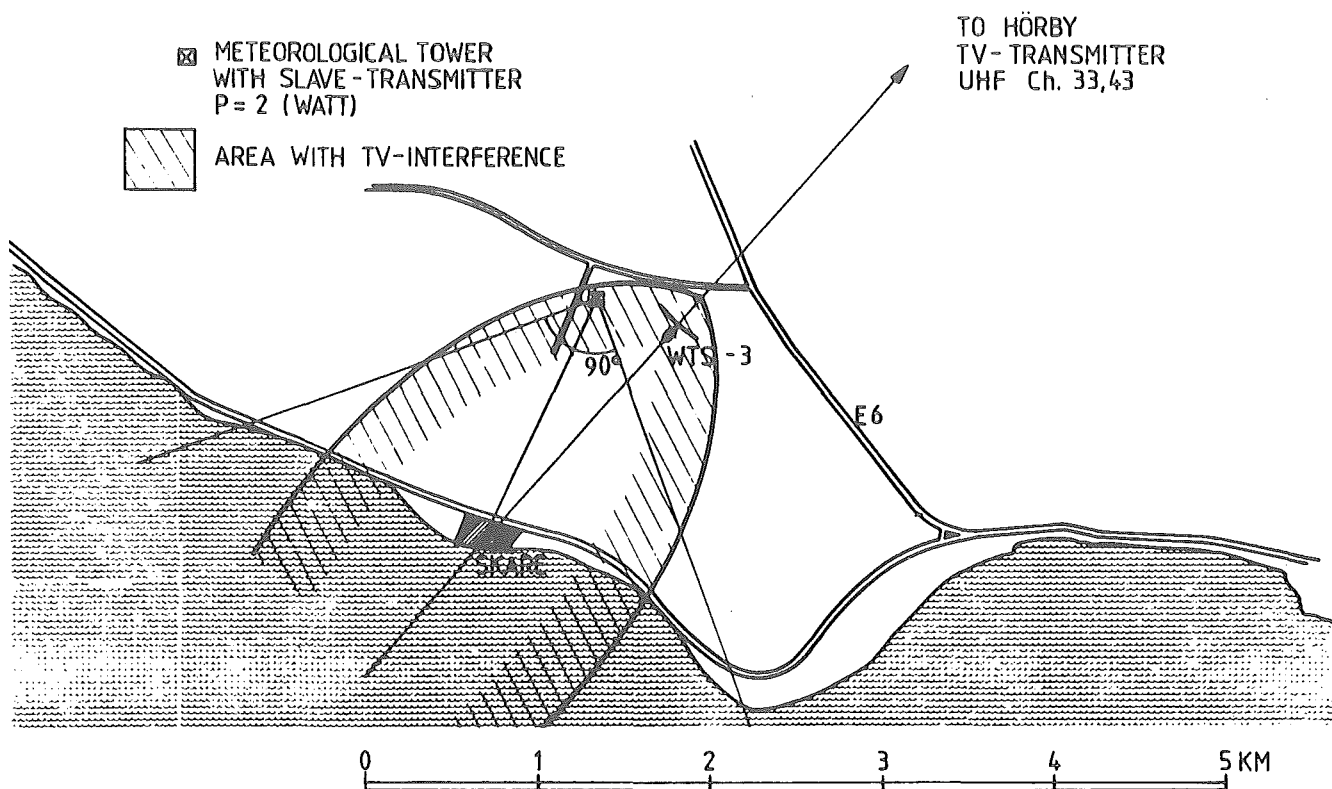
Figure 9   Map of Maglarp and surroundings

The experiances from the first three months after
installation of the transmitter have been good.

The interference problem in the village Skåre is
solved.

The covered area of the transmitter is possibly too
narrow. There are still complains from people
living outside the area of the slave-transmitter
but with TV-interferences at some wind directions.

The cost of the transmitter is approx. 100.000:-SEK
and is paid for by the project at Maglarp.

The installation of the transmitter on the meteoro-
logical tower is only temporary because the con-
tract on the tower with the landowner, is limited
in time.

A special mast for the Slave-transmitter has to be
built wich adds approx. 30.000:- SEK to the cost.
The siting of the new mast is not decided yet.

References:

1   TV-interferensmätningar på Maglarp vindkraft-
        verk 1984-01-25, Teght - Sundberg.

2   TELE No 2, 1980
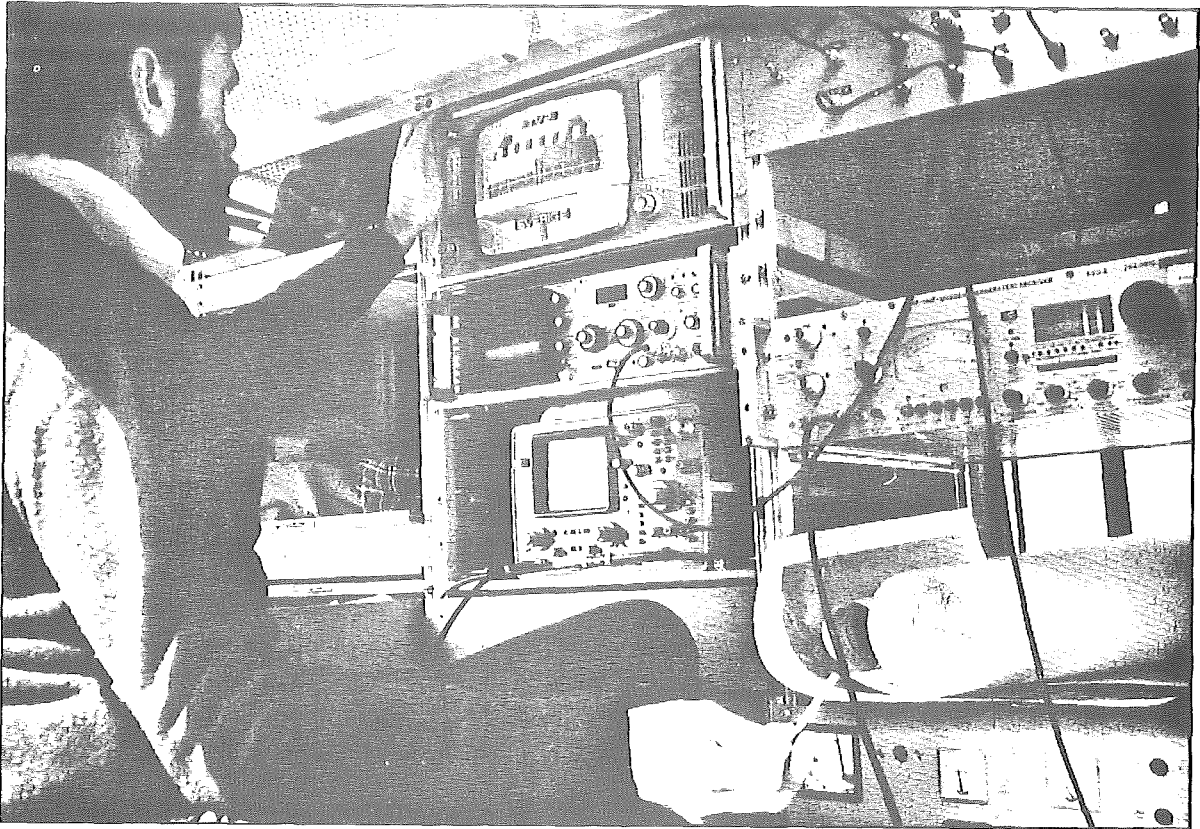
Ulf Tegth

TV-Interference measurements at Kalkugnen test windmill

Specular and forward scattering from rotating blades result in interfering amplitude pulses. TV-pictures can be corrupted by intensity fluctuations and synchronization jumps.

Field tests at the Kalkugnen windmill have given just perceptible interference from the most severe case, i.e. coherent forward scattering, at an extrapolated distance from the blades of about 400 meters near the maximum coverage range of an UHF TV-transmitter, and about 140 meters within line-of-sight. The backscatter limit within line-of-sight of an UHF TV-transmitter has been measured at 80 meters. The just perceptible interference protection ratio was found to be 28 dB.

For the next generation of wind turbine generators the expected interference radii with metal

blades for forward scattering are 7.2 km and for backscattering 2.8 km yielding 90 % of locations. The corresponding radii with fiber blades containing a thin wire will be 2.6 km and 0.5 km respectively.

Specular and forward scattering from rotating blades

Total received field strength

At the receiver input the total field strength will consist of a direct wave, sometimes diffracted by an obstacle, from the transmitter and scattered contributions from the vicinity of the antenna. Large metal surfaces compared with the wavelength, like airplanes and rotating blades, result in a time varying amplitude and phase of the received signal. The terrestrial TV system carries the picture information by using amplitude modulation and is more likely to be corrupted than frequency modulated systems like sound broadcasting.

Modulation function index and width

An electromagnetic wave transmitting TV signals is usually horizontally polarized, i.e. the electric field component lies in the horizontal plane. This field will give rise to currents in conductors, especially good in metallic surfaces with horizontal extension. These currents in turn will give rise to new fields concentrated perpendicular to the surface. Rotating blades will therefore give rise to a scattered wave each time the blades are horizontal. Optical physics can be applied to large surfaces relative to the wavelength and the received pulses will be of sin x/x-type with time. The resulting envelope variation is a measure of the modulation index, i.e. the voltage ratio of undesired to desired signal.

Field tests at the windmill in Kalkugnen

Scattering tests

With the blades locked in their four extremes, the turbine was rotated around its vertical axle. The gain function, i.e. the scattering area of the windmill, was measured in various directions.

Operational tests

With the blades rotating around their horizontal axle the windmill is self-oriented towards the wind. The two blades form some small angle relative to the vertical rotating plane, so only one blade will give a disturbance at each time. The envelope variation by the resulting wave was measured at various sites,

especially in front of and behind the windmill relative to the transmitter. The sound carrier was used for envelope detection. Also the modulation function pulse width was measured between the first nulls.

Calculation of windmill interference zone

Aperture scatterer

The zones containing unacceptable interference will be a cardioid towards the transmitter for specular reflection and a sine for forward scattering. For a dipole antenna and line-of-sight wave transmission the radii are given from

$$4 \pi r/\lambda = \sqrt{S/I} \times 4 \pi a/\lambda^2$$

resulting in

$$r = r_1 = r_2 = a/m_i \lambda$$

where a = blade area, gain = $4 \pi a/\lambda^2$
m_i = modulation index = $\sqrt{I/S}$
I = interference power (scattered field)
S = signal power (direct field)
λ = wavelength

(T. Senior, D. Sengupta and J. Ferris, 1977)

The lobe width between the first nulls of $sin \pi x/\pi x$, $x = \theta/\theta_0$: $2 \theta_0 = 2 \lambda/l$, where l = blade length.
For Kalkugnen we expected:
Area $a = 5.1 (m^2)$
Wavelength $\lambda = 0.57 (m)$, $f = 524.75 (MHz)$
Distance d = 21 (km) (Gävle — Kalkugnen)
Modulation index m = $0.1/\sqrt{10}$, i.e. $S-I = 30$ dB
$r_1 = r_2 = 293(m)$, $a/m\lambda$ $d \leqslant l$.
Lobe width $2\theta_0 = 7°$, length $l = 9(m)$
    For a directional antenna like a Yagi with a front-to-back ratio of 15 dB we get $r_1 = r_2/\sqrt{30} = 52(m)$, which is a more realistic case than with an unidirectional antenna.

Linear scatterer

If the cross dimension (width) of the reflecting conductor is small as compared with the wavelength, and the other dimension (length) is much greater than the wavelength, the scatterer can be treated as linear. Coherent scattering in free space for the direct and reflected wave will give

$$4 \pi r/\lambda = \sqrt{S/I} \cdot 2 l/\lambda$$

where r = distance blade — receiver, fig. 2.
    l = length of linear scatterer.
    The gain of a linear antenna $g = 2 l/\lambda$, $l \geqslant \lambda$.
    Introducing the protection ratio
$R = 10 \, log(S/I) = -20 \log m = 30dB$, $m_i = 0.1/\sqrt{10}$
we can write the interference zone radii

$$r = (l/2 \pi) 10^{R/20} = 51 = 45(m)_1 \, l = 9(m)$$
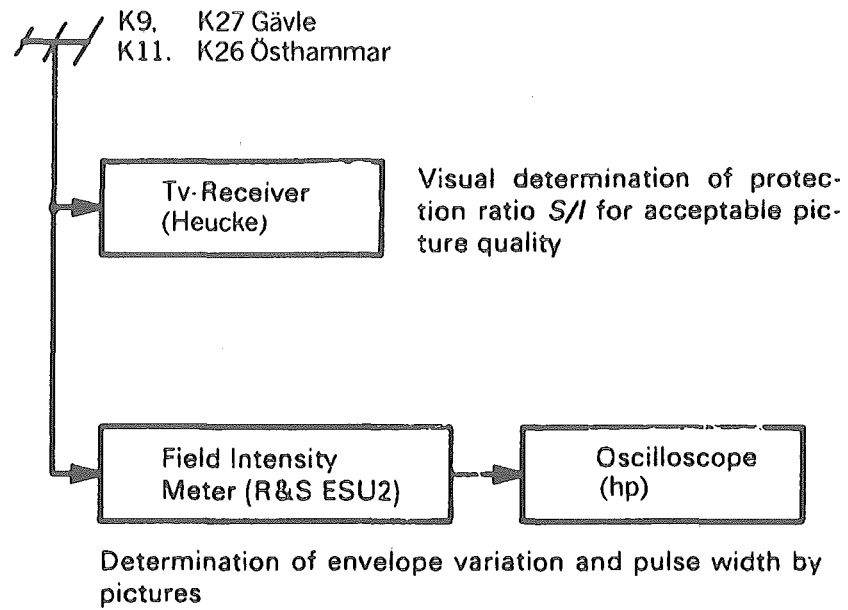
Figure 1. *The measuring equipment installed in a van.*

T = Transmitter,   B = Blade,   R = Receiver
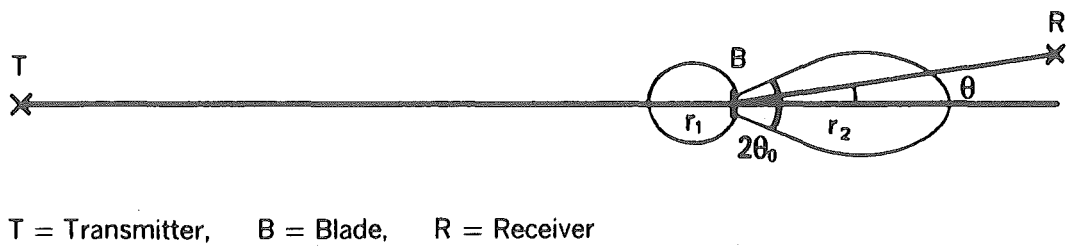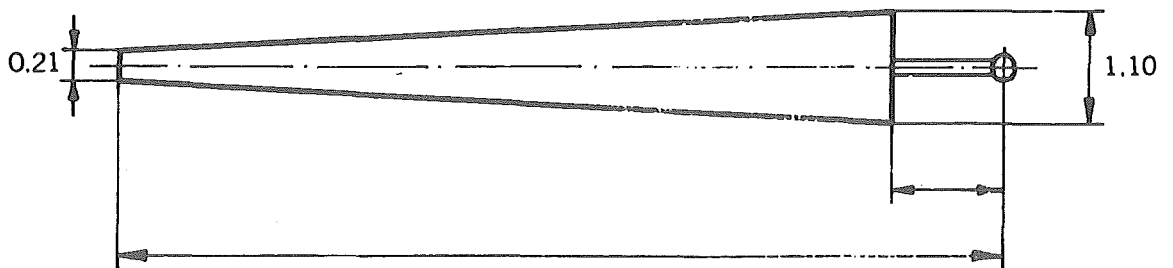
Figure 2.

Figure 3. *Blade geometry(m)*

Protection ratio

The protection ratio in dB, $R = S - I$, where S = signal power level and I = interference power level, has a statistical distribution. The reflected interference power and the direct signal power can be described by a log-normal distribution as due to long-term effects. The variability with location can here approx. be found to have a standard deviation $\sigma = 3$ dB for wood, and $\sigma = 1$ dB for plain. The variability in time can be left out due to positive correlation for almost the same transmission paths.

(Å. Blomquist and L. Ladell, 1974).

If the smallest receiver protection ratio R_o shall be fulfilled for at least 90 % of the locations similar to land mobile coordination, the median value for wood will be

$R_m = R_o + 1,3\,\sigma\,\sqrt{2} = 28 + 5 = 33$ dB
[CEPT Rec T/R 35]
$R_o = 28$ dB for just perceptible interference
$\sigma = 3$ dB for transmission loss local variability in wood (FOA 3)

Height gain

The median smooth spherical Earth propagation factor can be expected in CCIR Rec. 370-3 giving the following estimates for Kalkugnen test site: (90 % resp. 50 % of the locations exceed the just perceptible interference limit $R_o = 28$ dB).

Transmitter	Gävle		Östhammar	
Percentage (%)	90	50	90	50
Distance d (km)	21		55	
Wavelength (m)	0,58		0,59	
Tx ant. height h (m)	325		331	
Roughness Δh(m)	10		20	
Rcvr ant. h_2 (m)	10		10	
Prop. factor F_2 (dB)	0		−22	
Tower height h_3 (m)	24		24	
Prop. factor F_3 (dB)	0		−12	
Prot. ratio R_m (dB)	33	28	33	28
Height gain $F_m = F_3 - F_2$ (dB)	0		10	
Aperture radii r_2 (m)/ r_1(m)	414/74	233/42	1221/217	687/122
Linear radii r_2 (m)/r_1(m)	64/11	36/6	202/36	114/20
Scatter area a(m²)	5,1		5,1	
Scatter length l (m)	9		9	
Lobe width $2\theta_o$ (°)	7		7	
Front-to-back ΔG (dB)	15		15	
Field-strength E (dBµV/m)		111		81

Table 1.

The interference zone median radii boundaries:

a) Aperture

$r_m = (a/\lambda)\ 10^{(R_m + F_m - \Delta G)/20},\ l \geqslant \lambda,\ b \geqslant \lambda$
where
a	= scattering area (m²), $a = l \cdot b$
λ	= wavelength (m)
R_m	= median protection ratio (dB)
$F_m = F_3 - F_2$	= median height gain (dB)
ΔG	= receiver antenna front-to-back ratio (dB)

b) Linear

$r_m = (l/2\,\pi)\ 10^{(R_m + F_m - \Delta G)/20},\ l \geqslant \lambda, b \geqslant \lambda$
where l = scattering length (m)
   b = scattering width (m)
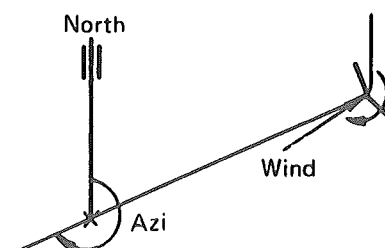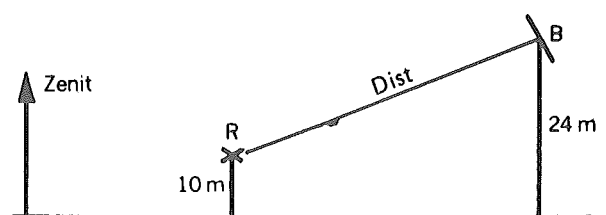
Figure 4. Test site

Operational tests of Gävle TV2 1978, July 11th

Point	Dist (m)	Azi (°N)	Wind (°N)	Ant	Δ (dB)	S-I (dB)	Observation
1	70	280	25−55	HD	—	—	No perturbation
3	38	255	25−55	HD	3	15	$\Delta_1 = 1.5$, $\Delta_2 = -1.5$ dB

Scattering tests at Gävle TV2 1978, April 12th

Backscatter (Static measurements)

3	38	255	HD	4	13	Gondola reflection
3	38	255	HD	5	11	Gondola only
3	38	255	HD	5	11	Gondola reflection
3	38	255	HD	—	—	Gondola only
3	38	255	HD	3.5	14	Fig. 5

Forward scatter (Static measurements)

5	50	86	LP	—	—	Short reflection
5	50	86	LP	6	10	Blade towards
5	50	86	LP	4.5	12	Sync. disturbance
5	50	86	LP	—	—	Vibration T or B
5	50	86	LP	3.5	14	Also intensity mod

Natural rotation TV2 270° Wind speed 8−14 m/s Fig. 6
Natural rotation TV1 270° Y 0.8 27 $\Delta_1 = 0.3$, $\Delta_2 = -0.5$ dB
No perturbation

Operational tests

Forward scatter from Gävle TV2 1978, April, 12th

Point	Dist (m)	Azi (°N)	Wind (°N)	Ant	Δ (dB)	S-I (dB)	Observation
6	50	94	270	LP	2	19	Wood scattering
6	50	94	270	Y	1.6	21	Fig. 7

Backscatter from Gävle TV2 1978, April, 13th

7	80	277	200	HD	0.8	27	Blade + gondola
7	80	277	267	HD	3.2	15	Fig. 8
7	80	277	267	LP	—	—	No perturbation
8	103	266	267	LP	—	—	Front-to-back = 13 dB

Forward scatter from Östhammar TV2 1978, April 13th

9	40	320	150	LP	2,3	18	Sync. disturbance
9	40	320	140−185	LP	3,5	14	Very disturbing
10	90	320	140−150	LP	3	15	Fig. 9
10	90	320	140−185	LP,	2,3	18	Fig. 10
10	90	320	140−185	LP	1,5	21	Fig. 11
10	90	320	140−185	LP	0,7	28	Just perceptible
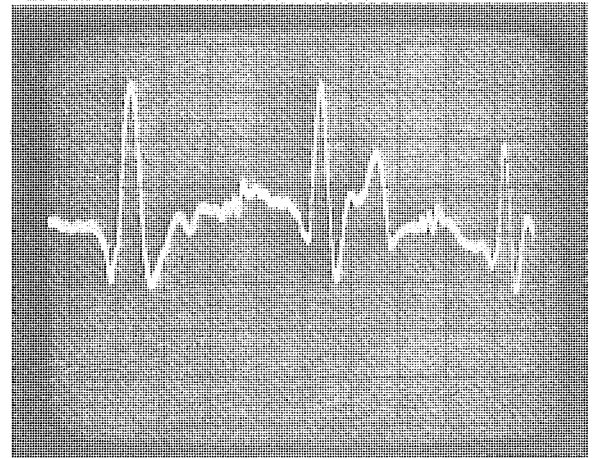
Figure 5. Point 3, phase 5, backscatter, hor. dipole, distance 38 m, $\Delta_1 = 3.5$ dB. The blades rotate at low speed behind the gondola. Sweeptime 0.5 s/div. together with normal reflection occurrence $2 \cdot 77$ rpm $= 2.57$ Hz results in time between the first nulls $2\tau = 0.05$ s. TV2 Gävle
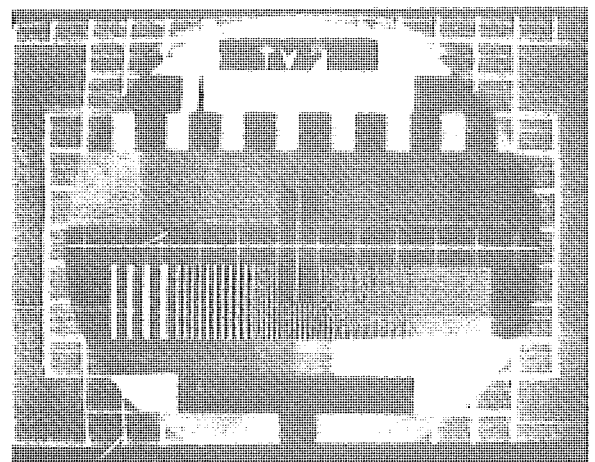
Figure 6. Point 3, forward scatter, log. per. dipole, distance 50 m, sync. disturbances (vertical jumps). TV2 Gävle

Measurement results at Kalkugnen 1978, July 11th−14th

Measurement with 2T-pulse was omitted because of too short at time difference between direct and scattered waves, even at backscatter, and that the transmitter had some overshoot.

Legend
Point: Measurement point 1.
Dist. (m): Distance between blade and receiving antenna
Azi. (°N): Azimuth from blade to receiving antenna
Wind (°N): Wind direction
Ant.: HD = Horizontal dipole antenna
  LP = Logarithmic periodic
  Y = Yagi, TV1
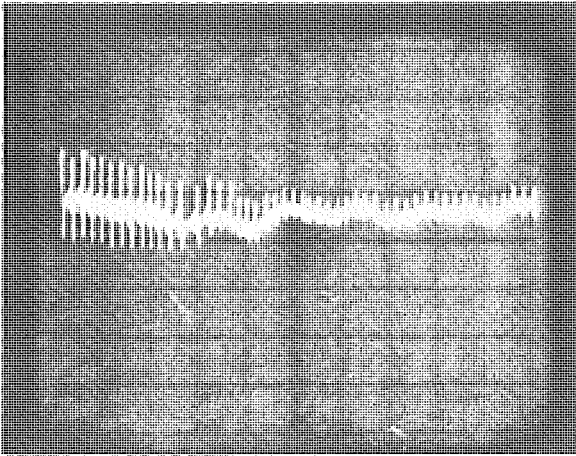
Figure 7. Point 5, forward scatter, Yagi, TV1, Distance 50 m,
$\Delta_1 = -\Delta_2 = 0.8 dB$, sweep time 2 s/div.
  No intensity fluctuation could be identified because of equal positive and negative pulses.
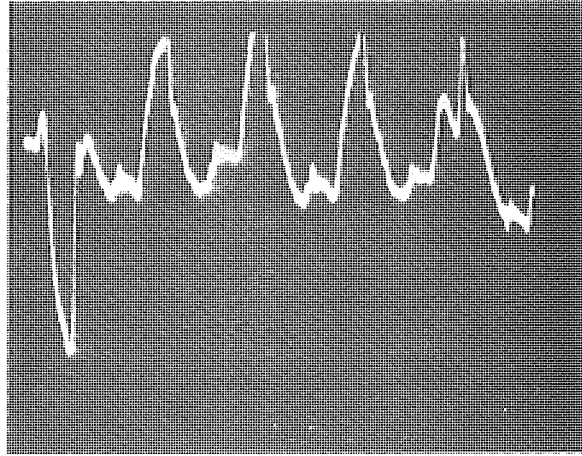
Figure 8. Point 7, backscatter, hor. dipole, distance 80 m,
$\Delta_1 = 2.5 dB$, $\Delta_2 = -3.2 dB$, sweep time 0.2 s/div.
  Change from negative to positive pulse because of a small change in wind direction. TV2 Gävle
  Field strength 86 dB (μV/m).

Envelope variation and signal-to-interference ratio

The envelope variation around the direct field (sound carrier) in dB
$\Delta_1 = 20 \ log \ (1 + m_i \ f(t))$
$\Delta_2 = 20 \ log \ (1 - m_i \ f(t))$
where m_i = modulation index, $f(t)$ = modulation function
The max-min-variation in dB
$\Delta = \Delta_1 - \Delta_2 = 20 \ log \ [(1 + m_i f(t))/(1 - m_i f(t))]$
where $f(t) \leqslant 1$, $m_i = \sqrt{I/S}$ defined in 3.1
Thus
$m = (10^{\Delta/20} - 1) / (10^{\Delta/20} + 1)$
Signal-to-interference ratio in dB
$S - I = -20 \ log \ m_i$

Summary of measurement results

The rotating blades gave TV picture corruptions resulting in intensity fluctuations and even synchronization disturbances with vertical jumps. In the field tests with forward scattering the just perceptible interference occurred at $S\text{-}I = 28$ dB. Att $S\text{-}I = 20$ dB (U.S. report) sync. disturbances were present, which are very annoying.

The pulse width between the first nulls was registered to between 0.04 and 0.12 seconds. Because of no automatic gain controll (AGC) action, these pulses can be simulated in the laboratory on video frequencies with short pulses low pass filtered with 3 dB bandwidths between 50 Hz and 17 Hz. Thereby the limit for acceptable interference could be better justified.

Specular reflection can be expected with a scat-

tering area almost reaching the physical blade area, as long as the dimensions are much greater than the wavelength. With a thin blade compared with the wavelength we can use linear scattering estimates. The interference distance will however be reduced by using a typical Yagi antenna with a front-to-back ratio in ordinary terrain of about 15 dB. Without such a directional antenna the picture will suffer from synchronization problems, even without the windmill. By influence of the Earth's curvature the field strength beyond the line-of sight limit will be smaller with the antenna height resulting in the interference distance to be somewhat greater. The backscatter just perceptible interference limit for line-of-sight from Gävle was measured at 80 meters.

Coherent forward scattering is difficult to estimate because the scattering area is always a fraction of the physical blade area. In the measurements done only the resulting signal was registered, why it is not possible to distinguish between scattering area reduction and height gain increase. However, median height gains can be expected from CCIR propagation curves, yielding a course estimate of this fraction to 30 %. Furthermore the width of the actual blade (fig. 3) varied between half and double the wavelength being used, giving a calculation problem between aperture and linear scatter. The sample measurements also result in an extrapolated interference limit for forward scattering from Östhammar of about 400 metres and from Gävle about 140 metres. VHF TV interference is less severe than UHF at the same distance.
Helicopter measurements have shown the height gain to vary between 0 and 20 dB independent of distance due to diffraction or free space multipath propagation together with transmitter antenna gain function.

Conclusion

Reflections from rotating metal blades result in TV-picture intensity fluctuations for signal-to-interference ratios less than 28 dB, and synchronization jumps below 20 dB.

The contour described by just perceptible interference for a given amount of locations is a sinusoid for forward scattering relative to the transmitter and a cardioid for backscattering. The sinusoid lobe width between the first nulls is for Kalkugnen 7° and for the next generation 2°.

The interference radii are for the metallic blade of Kalkugnen for forward scattering 370 metres and for backscattering 215 metres estimated for 90 % of the locations that are free from interference on a circle dividing the coverage area for UHF TV into two equal areas. Corresponding radii for the next generation of wind turbine generators are 7.2 km and 2.8 km, taking the worst case forward scattering area as 30 % of the physical blade area like the Kalkugnen case. The backscatter radii are reduced by the receiver antenna front-to-back ratio of 15 dB.

The radii causing interference for 50 % of the locations are for Kalkugnen 205 metres and 120 metres, and for the next generation 6.5 km and 1.6 km.

Figure 9. Point 10, forward scatter, log. periodic, distance 90 m $\Delta_1 = 1\,dB$, $\Delta_2 = -2\,dB$, sweep 1 s/div. TV2 Östhammar.
Field strength 84 dB ($\mu V/m$).

Figure 10. Point 10, forward scatter, log periodic, distance 90 m $\Delta_1 = 1\,dB$, $\Delta_2 = -1.3\,dB$, sweep 0.1 s/div. TV2 Östhammar.
Pulse width $2\tau = 0.04$ s.

Table 2. Wind turbine generators. Interference radii for an actual proposal to wind turbine generator based on Kalkugnen measurements will give the following estimates

TV-transmitter (Tx)	Gävle		Östhammar	
Percentage of locations (%)	90	50	90	50
Distance (Tx-B) d (km)	21	21	55	55
Frequency f (MHz)	519,25	519,25	511,25	511,25
Wavelength $\lambda = 300/f$ (m)	0,58	0,58	n0,59	0,59
Tx ant. height h_1 (m)	325	325	331	331
Terrain height Δh (m)	10	10	20	20
Receiver (Rc) antenna h_2 (m)	10	10	10	10
Propagation factor F_2 (dB)	0	0	-22	-22
Tower (B) height h_3 (m)	75	75	75	75
Propagation factor F_3 (dB)	0	0	-2	-2
Height gain $F_m = F_3 - F_2$ (dB)	0	0	20	20
Protection ratio R_m (dB)	33	28	33	28
Forward scatter area a_2 (m²)	20	20	20	20
Aperture radii $r_2 \sim a_2/\lambda$ (m)	1624	914	7,2 km	6,5 km
Line-of-sight (B-Rc) d_f (km)	5	5	4,5	4,5
Backscatter area a_1 (m²)	65	65	65	65
Aperture radii $r_1 \sim a_1/\lambda$ (m)	943	535	2766	1555
Front-to-back ratio ΔG (dB)	15	15	15	15
Blade length l (m)	37	37	37	37
Linear radii $r_2 \sim l$ (m)	263	148	2626	1482
Linear radii $r_1 \sim l$ (m)	45	25	468	260
Lobe width $2\theta_\circ \sim \lambda/l$ (°)	1,7	1,7	1,7	1,7

For the KMW prototype with metal blades on Southern Gotland, an estimation of the half circle cardioid radius, $r_1 = 3$ km (cf. Fig. 12 Sengupta and Senior, 1979). For the Karlskrona Warf prototype at Trelleborg the estimate is $r_1 \cong 0.6$ km due to Al-tape lightning protection on fiber blades. This distance is also the limit for a household to an actual wind turbine. For Nordsat at 5°E above the Equator about the same half circle cardioid zones towards the South must be taken into account as for UHF-TV, but the forward scattering zones will be well within the 0.6 km radius.
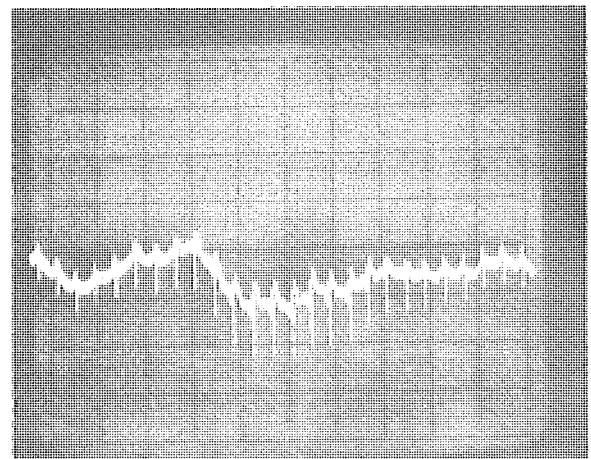
Figure 11. Point 10, forward scatter, log. periodic, distance 90 m,
$\Delta_1 = 0.5\,dB$, $\Delta_2 = -1\,dB$, sweep 1 s/div., TV2 Östhammar
Just perceptible interference·at the edges of the picture with $\Delta_1 = 0.3\,dB$, $\Delta_2 = -0.4\,dB$.

The aperture scattering radii are proportional to the frequency giving values for VHF 200 MHz one third of the values given for UHF 600 MHz. The lobe width is inversely proportional to the frequency. A linear scatterer in the form of a thin wire gives radii independent of frequency.

Coherent scattering is caused by a common area of one blade in horizontal position visible both from the transmitter and the receiver. Forward scattering uses only some fraction, e.g. 30 %, of the physical blade area at the lower side depending on blade angle, edge curvature relative to wavelength and blade length (cf. radar cross section for a cylinder). Backscattering area is in the worst case almost equal to the physical area. If needed, complicated calculations of scattering areas from various bodies can be made.

A blade with a conductor that is thin relative to the wavelength can be treated as a linear scatterer. The 90 % radii for Kalkugnen forward scattering are estimated to 200 meters and backscattering to 35 meters, which can be compared with those of aperture scattering 370 meters and 215 meters. Similar linear scattering from the next generation of wind turbine generators is expected to give radii of 2.6 km and 0.5 km, compared with aperture scattering radii of 7.2 km and 2.8 km. The interference area can thus be considerably reduced by introducing fiber blades containing a thin wire, and the area can be nil with pure non-conducting material.

The interference radii are proportional to the blade length, but the forward scattering lobe width is inversely proportional to the blade length. Furthermore, the radii are proportional to the square root of the tower height when the propagation from the transmitter to the blade is diffraction over spherical Earth. This is the case for the next generation of wind turbine generators at the outer half of the covarage area. For line-of-sight propagation the radii are independent of height.

The mean distance between high power UHF TV-transmitters can be found to be about 60 km. The coverage area radius is expected to be 70−80 km (for interdecile terrain height 10−20 m, effective radiated power 1 MW, transmitter antenna height 300 m, receiver antenna height 10 m, minimum field strength 3 mV/m, median transmission loss). A circle halving the coverage area will have an average radius of $75/\sqrt{2} = 53$ km, which is close to the distance Östhammar−Kalkugnen (55 km). Thus there is some overlap between the coverage areas from different transmitters.

There are several ways of eliminating interference, e.g.:

a. to move the antenna outside the forward scattering sinusoid lobe (typical width of the lobe is $r_2\lambda/l$ = 130 meters for the next generation);
b. to use a better antenna site with a greater front-to-back ratio than 15 dB ($\Delta G \cong 20$ dB) inside the backscatter cardioid;
c. to install cable-TV in highly populated areas because of lack of TV radio channels in certain regions;
d. to install a smaller TV-transmitter below the lowest point of the blade (about half the tower height), which costs about SEK 250 000:− (1978/79) and can only be used in exceptional cases because of frequency channel shortage;
e. to receive another TV-transmitter within overlapping coverage areas, if the same programs are transmitted (e.g. regional TV).

References

A. Blomquist and L. Ladell, 1974,
Prediction and Calculation of Transmission Loss in Different Types of Terrain,
FOA3 Report C 3792-E2, June

CCIR, International Radio Consultative Committee

CEPT, The Conference of European Posts and Telecommunications

T. Senior, D. Sengupta and J. Ferris, 1977,
TV and FM Interference by Windmills,
University of Michigan, College of Engineering, Department of Electrical Engineering, Radiation Laboratory Report 014438-1-F, February.*

* D.L. Sengupta f T.B.A. Senior, 1979,
Electromagnetic Interference to Television Reception Caused by Horizontal Axis Windmills, Proc. IEEE, Vol. 67, No. 8, August.

Ulf Tegth, Frequency Planning Office, Radio Division, Swedish Telecommunications Administration

NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD

ENVIRONMENTAL MONITORING

BURGAR HILL, ORKNEY

WIND TURBINE GENERATOR SITE

AND

SIMILAR WORK AT OTHER UK WTG SITES

INTRODUCTION

Contained within the Conditions of Approval given by the Secretary of State for Scotland in June 1981 to the Board's application under Section 2 of the 1909 Electric Lighting Act for the installation of one - 250 kVA and three - 3 MW wind turbine generators on Burgar Hill, Orkney were actions agreed by the Board to be taken with regard to environmental monitoring. These actions were agreed in consultation between the Board, the Orkney Island Council, the Nature Conservancy Council and the Royal Society for the Protection of Birds. The Approval was extended in 1983 to include a 300 kW unit. The 250 kW and 300 kW units were installed in mid-1983 and the first 3 MW unit is expected to be installed during 1985/86. There are three categories of monitoring namely electromagnetic interference, birds and noise. This note gives a progress report and up-to-date situation on each of the programmes.

Also included are details of the environmental monitoring being carried out by the Central Electricity Generating Board at the site of their 200 kW wind turbine generator at Carmarthen Bay, Wales and the site of their future multi-megawatt unit at Richborough in Kent. An outline of environmental study work being carried out under the auspices of the UK Department of Energy is also given.

ELECTROMAGNETIC INTERFERENCE

It was considered essential to establish validated data on existing TV signal strengths in the area for comparison purposes after the installation of the proposed 250 kW, 300 kW and 3 MW wind turbine generators.

The Board's engineers in conjunction with British Telecom carried out tests in the area of Burgar Hill on 18 August 1981.

The tests conducted at 21 different locations (See Appendix 1) comprised of a visual assessment of picture quality as well as a measure of the signal as fed from the consumers aerial into his receiver. A survey of signal strength in the area was not included in the tests and it should be noted that the results are dependent on the consumers equipment. Appendix 2 contains the test results.

A guide to the basis used for the visual assessment of picture quality is as follows:

        5 - Perfect picture
        4 - Minor faults only detected by close scrutiny
        3 - Minor ghosting and/or snow
        2 - Severe ghosting and/or snow picture breaking up
        1 - Below threshhold for colour reception

The measured signal is quoted in dB above a reference level $1 \mu V/m$. It should be noted that due to the use of varied aerial and amplifier combinations that a high signal level does not necessarily imply good reception.

The results obtained conform closely to the predicted service area shown on BBC Information Sheet 4967(1) November 1974 covering their Keelylang transmitter. (Appendix 3 attached).

Test 11 in Appendix 2 was carried out using a log-periodic aerial owned by the Board and mounted on British Telecom's 25 ft mobile mast. This will provide a reference for future tests.

In submitting their report British Telecom pointed out that all the houses in the shadow of Burgar Hill are outside the area of the television transmitter and that any marginal change in TV signals due to the presence of wind turbine generators would have a very noticeable effect on the reception.

Correspondence with both BBC and IBA revealed that, despite recognising that there were some local reception problems in the area concerned, there were no plans at that time to instal any relay stations in the Orkneys.

On 5/6 November 1981 the BBC Research Dept visited Orkney for the purpose of:

(a)   Updating their normal coverage survey which was last carried out in 1977.

(b)   To take a series of measurements in anticipation of any interference which could be caused by the wind turbine generators on Burgar Hill.

The main difference in the tests carried out by the BBC, with the Board's engineers in attendance, was that whilst British Telecom made their measurements of signal strength and picture quality using the viewer's aerial and TV set the BBC used their own Log Periodic Aerial and colour receiver. Another difference of course was that the BBC equipment was of a higher quality in colour receiver, signal strength instrument and the aerial which was flexible. It follows therefore that the BBC results are better in signal strength etc than those of British Telecom. Another factor is that some of the viewer's aerials are in "just fair" conditions due to long exposure to the Orkney weather.

A significant change in the TV reception of the area coincided with the tests in that a self help scheme was brought into use. An active repeater sited on Vishall Hill (see Appendix 1) was switched on, the transmit aerial, vertically polarised, being directed in the general direction of Costa Hill to the west. The coverage of this self help scheme is bounded by the area covered by test locations 1 to 5 and 13 to 16. This was the area which was previously getting poor reception or in some cases no reception at all from the Keelylang transmitter. It is felt that this self help scheme is to the mutual benefit of the national broadcasting authorities and the Board especially since the aerials will now be directed away from Burgar Hill.

The results of the measurements and assessments of received picture quality as determined by the BBC Research Division are given in Appendix 4 attached together with a list of the equipment used. The aerial was elevated to 10 m agl and the vehicle positioned as close as practical to viewers installations. The locations were numbered as shown in Appendix 1 to correspond to domestic installations which had earlier been assessed by the Board and British Telecom. Picture degradation from delayed images was assessed according to the CCIR5 grade impairment scale as follows:

Grade 5 Inperceptible
Grade 4 Perceptible but not annoying
Grade 3 Slightly annoying
Grade 2 Annoying
Grade 1 Very annoying

Field strength is given in dB relative to 1μV/m.

In their assessment of the degradation likely to be caused to television reception by the installation of large wind turbine generators the BBC Research Dept used the co-efficient of the reflection of the wind turbine generator as follows:

$$\frac{\lambda}{A \sin \theta}$$

where A is the area of the blades in square metres and θ is the angle of reflection.

The path profile between Keelylang Hill transmitter and Burgar Hill is shown in Fig 1. The measured field strength of Keelyland Hill at the site was approximately 83 dB (μV/m) at 10 m agl and it is predicted that the signal level will be significantly higher at and above the centre of the 60 m diameter machine. For the assessment of interference 95 kB (μV/m) was taken as the amplitude of this incident field and the blade area (A) assumed to be 100 m^2. D is the distance between the wind generator and viewers installations. All installations in the district are line of sight to Burgar Hill and there are no terrain losses.

An assessment of the field strength (FS) of the reflected signal at location 23 is as follows:

$$FS = FS \text{ at generator} - 20 \log D + 20 \log \frac{\lambda}{A \sin \theta}$$

$$= 94 - 20 \log 3.2 \times 10^3 + 20 \log \frac{0.45}{100 \sin 10°}$$

$$= 94 - 70 + 32$$

$$= \underline{56 \text{ dB}} \ (\mu V/m)$$

From Appendix 4 the amplitude of the direct signal at location 23 from Keelyland Hill is 70 dB (μV/m).

At the receiver input, the interfering signal will be 14 dB below the wanted signal. The visibility of delayed image signals is somewhat dependent on the time delay, but if the delay is more than about 0.75 m sec a difference of about 30 dB between signals is required for a Grade 5 picture. The calculated time delay between the signals at location 23 is 1.7 m sec and it was concluded that it is almost certain that reflections from the blades of the 60 m machine will result in Grade 2 to 3 interference. The rotating blades will cause pulsating interference which is likely to be more annoying to viewers than a steady level delayed image.

From the analysis of the measurements given in Appendix 4 the BBC Research Dept predict that the blades of the 60 M wind turbine will cause delayed images at some 65 installations within the shaded area on Appendix 1. The field strength of Keelylang Hill at these locations is below the nominal limit of 70 dB rel 1 μV/m for Broadcast services. However almost all the viewers have installed better than average receiving systems and it is estimated that about 50% of them can receive satisfactory pictures which are better than Grade 3. The predicted additional pulsating interference from the 60 M wind turbine will undoubtedly result in complaints from these viewers. For the remaining 50% reception is already very difficult because of low field strength and reflections from the surrounding terrain and the additional interference will be much less troublesome.

Interference from the 20 M machine was predicted to be significantly less for two reasons. The incident signal will be lower because the signal path to Keelylang Hill is obstructed and the blade area is smaller. Both factors will result in a total reduction of about 14 dB in the reflected signal.

Coverage of the community operated transmitter at Vishall Hill is limited and is unlikely to provide an alternative to viewers affected by interference from the wind turbine. it was considered that there would be no interference to reception of the community transmitter.

The BBC Research Dept concluded that consideration should be given to the provision of an alternative service to the area.

Early in May 1982 Board's engineers had a meeting with representatives of the IBA and BBC to discuss the findings of the BBC Research Dept. It was agreed that there was some merit in considering the installation of a relay station to provide an alternative service to the area with the cost being shared by the IBA, BBC and the Board.

It was agreed that the installation of a new relay station should take place before the 3 MW unit was operational. However, once the 250 kW and 300 kW units were commissioned complaints of televising interference were received from households bounded by the area covered by test locations 6, 7 and 8. The interference took the form of bright and dull pulses coincident with the rotational speed of the turbine blades and worst when the blades of the machines was at 90° to the signal. Both machines caused the problem.

In the latter part of 1983 operation of the machines was precluded during the winter for a few weeks while a temporary solution was sought. Early in 1984 an active deflector (AD) was installed by the Independent Broadcasting Authority on the meteorological mast associated with the 300 kW unit. The AD consists of an aerial to receive the main transmitter of Keelylang Hill, at about 25 m agl; the signal is fed to a band pass pre-amplifier, followed by a wide band amplifier which feeds a transmitting aerial at about 4 m agl. The AD receives a horizontal polarised signal and transmits with vertical polarisation. This reduces the chances of the output of the AD feeding back to the input. It also reduces interaction between Keelylang Hill and AD signals at the domestic reception points, hence reducing the possibility of 'ghosts'.

This AD does not provide top grade pictures to the viewers previously affected but it has restored the signal to a quality better than obtainable by most of these viewers before the wind turbines were installed. There are still perhaps three households affected by pulsing in a narrow band bounded by test locations 6 and 7.

The Independent Broadcasting Authority have been working towards providing a permanent solution to those people in the area who have either no signal or a barely usable one. This lack of signal was not originally because of the wind turbines but a few houses have had their signal impaired by the two medium size machines and the situation is likely to worsen when the larger 3 MW unit is in operation.

The following work has been carried out by the IBA with a view to establishing the best position for a new TV relay station. The work is not yet complete.

a)   Terrain profiles were drawn to make a prediction for sites worth testing.

b)   Three sites were tested - one on Burgar Hill and two on Rousay. As might be expected none of these is a perfect solution to the problem. Burgar Hill has the problem that

    (i)   It needs to send out power over a wide arc, which can give more interference problems and requires a larger aerial system.

    (ii)   It needs to get its performance feed from a point on one side of the wind turbines and transmit from the other. Hence a long cable run and amplifiers are needed.

(iii)   Not all the "target" houses would be served. The Rousay site tests have taken place, but they have not yet been fully assessed. Again, they are bound to have the problem of not serving all of the target.

c)   The site test equipment consists of a specially built transmitter and a log periodic aerial on a pneumatic mast capable of being elevated to 30 m above ground level. This gives about 1 Watt of effective radiated power. (The final radiated power is liable to be more than this but scaling is applied. This also applies to the radiation pattern of the final aerial compared to the site test aerial).

An important aspect of the work currently being carried out by the IBA at and around the site at Burgar Hill is to learn about possible signal degradation resulting from wind turbines. This will enable the likely effects of any new proposals to be predicted.

One way in which wind turbies modify signals in an area is by re-radiating the signal incident upon them. Thus, direct and indirect signals arrive at a point and interact so that the resultant field level is either increased or decreased depending on relative phase, also 'ghosts' are produced because of a time delay. The wind turbine can thus be considered as a transmitter in its own right, but to treat it rigorously we would need to know the relative strength of the signal it radiates in all possible directions.

Some theories have been devised to try to answer these questions but they depend on assuming a simple geometry and simple composition of the blades. One theory assumes the blade to be a flat plate large enough to produce specular reflection. Another assumes a smaller thin plate where currents are also induced to flow on the opposite face so that forward and backward scatter occurs. A further assumption could be that the blade is rod like giving roughly equal radiation in all directions at right angles to the road axis.

The inadequacies of the theories, even for simple blade composition, make it necessary to carry out measurement campaigns to obtain confidence in any future predictions.

Observations in the area served by the AD did not show much dependency on the impairment on the direction of the spinner, but it was changing with blade angle. This does not give much support to the idea of specular reflection from a flat plate, but suggests that the radiation is more like that which would be obtained from a rod ie roughly equal radiation in all directions at right angles to the rod axis. However, it is likely that the truth lies between these two extremes.

Measurements made close to the wind turbines and looking through them towards Keelyland Hill, did not show any impairment when the receiving aerial was being crossed by the main part of the blade. However some impairment was observed when the feathering tips interrupted the path.

The measured magnitude of the re-radiated signal was of a sufficiently low level that it will only cause serious impairment if the direct signal is subject to significant attenuation.

BIRDS

Sections of the land in the near vicinity of the wind turbine generator site are either owned or leased by the Royal Society for the Protection of Birds and operated as bird sanctuaries. Both the RSPB and the Nature Conservancy Council feel that the construction period as well as the operating of the machines together with the noise produced could adversely affect the established pattern of habitation at and around the site. The Board share this concern and have been able to enlist the help and experience of the RSPB in carrying out a bird monitoring survey. The work started in May 1981 before the site started to be developed and will continue for at least one season after the first 3 MW machine is commissioned.

Two areas have been selected to give a comparison of the affects of the construction and operation of the wind turbine generators on Burgar Hill. Fig 2 indicates these areas where Plot A is adjacent to the siting of the generators and Plot B is sufficiently far away to be unaffected by it and will act as a control.

To facilitate the census work the moorland areas have been marked out in a 1 hectare grid system using posts with coloured tape. At least 10 visits are made to each plot in either early morning or evening to census what birds are present and holding territory. At the end of each season results are analysed using methods recommended by the British Trust for Ornithology. As methods will be the same each year it will be possible to compare the figures and assess changes. Linked with this will be an assessment of the changes in the land use or vegetation within the plots so that these can be noted when the summary is written up.

A report is produced before the end of each year summarising the results of the two plots together with any comments as outlined above. The work is carried out by staff of the RSPB and covers the period from April to June each year. The RSPB are being funded by the Board to carry out this work.

Site work was carried out during 1982 in the way of road works, installation of met masts, site accommodation, and civil foundations for the 250 kW wind turbine generator. This unit together with the 300 kW unit was installed in July 1983. Three seasons of census work is now complete. Foundation work and installation of the two machines took place outside the nesting season and the results of the census show no adverse affects on the numbers and types of birds present in Plot A adjacent to the site. The 1984 season census will reflect the affect of the two machines in operation and the site preparation work for the 3 MW machine. Census work will continue beyond the installation and operation of the 3 MW unit.

NOISE

Measurements are being and will continue to be taken for the first 2 years after the first 3 MW wind turbine generator is installed. These measurements will incorporate surveys along defined transects which have been determined by the Board in consultation with the Nature Conservancy Council and the Royal Society for the Protection of Birds.

The Board had a meeting in September 1981 with representatives of the NCC and RSPB and established the locations where the measurements were to be taken. 23 points were chosen as shown on Figs 3 and 4. These fall into 2 groups with 13 points in fairly close proximity to the site where measurements will help to evaluate the noise impact on birds. 10 points were chosen at greater distances from the site for community noise measurements.

The intention is to detect the complete 'foot-print' of noise across the full spectrum taking account of conditions of maximum travel of sound, ie weather conditions of maximum travel, sites with generally low ambient noise, and topography which enhances distance travelled.

The exercise is being conducted in 3 phases as follows:

Phase 1 (Pre-construction)

General levels of background noise in different weather conditions.

An initial set of readings was taken in Sept 1981. The instrument used was a B & K Type 2203 Precision sound level meter with Type 1613 octave filter. Readings were in dB and the noise was analysed by octave band analysis to indicate the component parts at various frequencies. Wind speed was measured by a hand held anemometer

manufactured by R W Munro Ltd. Reference data on wind speed and direction was received from Kirkwall Airport weather station. The results are shown on Tables 1 and 2.

Between Sept 1981 and July 1983 when the 250 kW and 300 kW wind turbine generators were installed further noise level readings were taken at regular intervals. The total number being in excess of 50. No octave band analysis however was carried out on those readings. The instrument used for noise was a B & K Type 225 Integrating Sound Level Meter with a B & K Type 4230 Acoustical Calibrator. The same hand held anemometer was used and reference data was provided by Kirkwall Airport weather station.

The results show that the background sound level varies for the same recorded wind speed depending on the weather conditions and the wind direction. As a generalisation however there is an increase of the order of 35dB(A) from 7 metres/sec to 27 metres/sec which is the operating range of the machines, ie approximately 2.5/3 dB(A) for each metre/sec increase in wind speed.

Early in April 1984 a set of readings was taken with both machines running and also with both machines shut down. The wind was from the South West and in the range 10-15 metres/sec at the site. At location 1 adjacent to the 250 kW machine the difference was 15dB(A). At the other locations close to the machines the highest difference was 5dB(A). At the locations remote from the site no difference was recorded.

Readings will continue to be taken at regular intervals in order to build up a data base.

Phase 2 (Construction)

The intention was to measure noise caused by construction work during different weather (principally wind) conditions and isolate and describe main sources of noise. The measurements were to be conducted in the same manner as Phase 1. This exercise proved difficult during the construction period of the 250 kW and 300 kW machines because of the intermittent construction noise, the variability of the wind and the dispersed nature of the locations for measurements.

The study of noise emissions from wind turbine generator sites requires the expenditure of considerable time and effort due to the vagaries of the weather, operational uncertainties, interference from other sources and the need to collect large quantities of data in order to describe noise environments in statistical terms.

A microprocessor controlled sampling system has been developed by the CEGB and utilised in field studies which permits the unattended collection of noise and other related data, in digital and analogue formats, within programmable limits using a range of control parameters. The system is known as PANDORA (Programmable Automatic Noise Data and Other Related Parameter Acquisition System) and is described in a paper by P G Nairne and M R Burt designated SWR/SSD/0381/N/84 Job No 05-67 and is available from the CEGB Central Library in London.

A version of this system was installed in April 1984 on Burgar Hill on the site of one of the future 3 MW machines. The location is approximately 250 metres east of the 250 kW and 300 kW machines and 350 metres north of the position of the 3 MW machine to be installed in 1985.

This equipment will be used to monitor the noise emissions during the construction phase of the 3 MW machine and supplement the continuing measurements described in Phase 1.

Phase 3 (Post Construction)

It is intended to measure the full spectrum of noise under different operational and weather conditions until 2 years after the 3 MW unit is put into service.

The PANDORA equipment will be utilised together with readings as described in Phase 1. Experience will determine whether the programme of measurements requires to be varied to acquire all details necessary of the noise spectrum.

CENTRAL ELECTRICITY GENERATING BOARD
ENVIRONMENTAL STUDIES

The CEGB installed in 1982 a 25 metre diameter 200 kW HAWTG at Carmathen Bay in South Wales. Statutory consent is being sought for a horizontal multi-megawatt machine with up to 90 metre diameter blades at Richborough in Kent. A brief review of the CEBB environmental studies follows:

ELECTROMAGNETIC INTERFERENCE

Following tests by the BBC around the machine sites at Carmarthen Bay (installed) and Richborough (planned) it is considered unlikely that these installations will cause problems although TV reception tests will be carried out after installation to confirm this conclusion.

BIRDS

The CEGB has adopted a policy of surveying early wind turbine sites to confirm that bird-strike effects are indeed small.

The site at Carmarthen Bay is being surveyed regularly by a local ornithologist as agreed with the Nature Conservancy Council. The bay area is acknowledged as important because of its widely dispersed population of sea ducks, and estuarial wildfowl, waders and other birds. No dead birds have been reported to date, although the period when the blades have been turning has been very limited because of operational problems. Similar arrangements are being made, via the Royal Society for the Protection of Birds for the site at Richborough. A two year survey programme is planned which should also provide data of value to future assessments.

NOISE

The prototype of the PANDORA sound measuring equipment described earlier in this paper was installed at Carmarthen Bay. Two commercially available outdoor microphase units are used, one (2-40 Hz) for infrasonic noise and the other for broad band noise (50-10000 Hz). The use of two channels was found necessary to accommodate the large signal dynamic range (approximately 60 dB) produced in this wide frequency band over the range of wind speeds of interest.

So far, noise background data has been recorded at two locations, one near a building and one over open grassland near the site. Some very interesting results have been obtained. Background varied by about 30 dB (A) over wind speeds of 3-15 metres/sec which is the operating range of the wind turbine. Human activity at this location appears to dominate noise sound pressure levels below wind speeds of 6 metres/sec, but winds control the background noise above that speed. Both sonic and infrasonic records showed background sound levels can vary significantly at, ostensibly, the same wind speed.

DEPARTMENT OF ENERGY
ENVIRONMENTAL STUDIES

VISUAL IMPACT

The Department of Energy have commissioned a firm of consultants to assess the visual impact of large wind turbines and the first report was submitted in Autumn 1983.

The principal objectives of this study were to apply the concepts and understandings of visual impact in general to wind turbines in the landscape. The study divided itself into essentially three parts.

Firstly, the aspects of visual impact were identified which are likely to be important and to need early study. It was concluded that the impact is likely to be significant in many, if not most, landscape types. Individual large turbines will be visually dominant for at least a radius of 1 km. The effect of groups of turbines and wind farms will be greater, particularly in open landscapes, but will also be different in kind. A single turbine may be the subject of curiosity whereas a large farm will probably take over the landscape. Transmission lines connecting a farm to a grid, access roads and other infrastructural components will add to the visual impact.

The motion of the blades will increase the impact compared to that of static structures. It will exaggerate the size and, particularly with a two-bladed turbine, will give the illusion of non-constant rotational speed which may be found to be disconcerting. The effects of blade motion appear not to have been studied so far.

Non-residents (ramblers, interest groups, etc) will need to be considered as well as residents. Indeed they may have the stronger adverse opinions. The attitude of residents will be influenced by whether they receive any direct benefit from the wind farm or whether the electricity is simply generated and "exported" for use by others. Other relevant factors will be their livelihood, attitude to nuclear power, etc.

Secondly, the possibilities for the mitigation of any significant adverse impact were reviewed.

The choice of site is likely to be more important than design and layout although these will nonetheless be important in themselves. Turbines as a whole will need to be carefully designed to achieve an elegance appropriate to the site and to give an impression of stability. It will be important to avoid the wrong colouring (dark, vivid or reflecting) but the choice of the right colour will probably not be critical.

Useful landscaping will be confined to treating the infrastructure and to screening in the immediate vicinity of points of view, residents' houses, etc.

Thirdly, the techniques appropriate to more detailed studies were reviewed. It was concluded that to adequately represent the visual appearance of wind farm to the public for evaluation will need a variety of techniques in combination. It was suggested that for a wind farm as a whole 360° panoramic static photomontage will be needed together with short video tapes simulating operating turbines in the landscapes in question. In addition it will be valuable to have more extensive film or video of existing installations in a variety of operating conditions.

This visual material can then be evaluated by a combination of social survey techniques. Initially a preliminary nationwide survey could be used to establish the general context in which wind farms in the landscape would be judged. Panels of members of the public could identify more specific issues of a visual character. Panels of experts and representatives of interest groups would establish a variety of trade-offs. Finally questionnaire surveys taking a larger sample of the public and examining their reactions in detail to a variety of hypothetical wind farms in differing landscape types could be used to quantify public reaction.

Studies were recommended to evaluate quantitatively the reaction to the siting of wind farms in a variety of different types of landscape and to compare this reaction with the reaction to well established forms of development such as transmission lines and motorways.

NOISE

Under the auspices of the Department of Energy a university is working in conjunction with a wind turbine generator manufacturer in developing a means of predicting near field noise produced by wind turbines.

A preliminary phase has been completed that consisted of a comprehensive review of existing methods, measurements on a 5 metre experimental turbine at Cambridge University and development of a simple predictive technique. The results agree qualitatively very well with the measurements.

The aims of the main project at present under way are to:

-       Collate appropriate theoretical propellor and wind turbine noise prediction formulae

-       Assemble a prediction programme and develop to a level at which comparisons with measurements may be made

-       Make measurements on the 250 kW machine on Orkney

-       Compare measured and predicted noise.

The university team visited the site on Orkney in late March 1984 and made comprehensive noise measurements which were synchronised to the on-site monitoring system. Work on the comparison of measured and predicted noise levels is currently underway.

ELECTROMAGNETIC INTERFERENCE

The Department of Enery is represented on the International Energy Agency's electromagnetic interference expert group by ERA Technology Limited. The expert group is currently drawing up recommended practices on the subject.

In addition, ERA Technology Limited, on behalf of the Department of Energy, is reviewing electromagnetic interference problems caused by wind turbine generators with the object of identifying radio services which may suffer degradation of performance.

ACKNOWLEDGEMENTS

The author wishes to thank the undernoted persons and organisations who provided material to be included in this Paper:

-       Mr R I Black, Service Planning Section, BBC, Research Department, Kingswood Warren, Tadworth, Surrey, KT20 6NP

-       Mr J Causebrook, IBA, Crawley Court, Winchester, Hants, SO21 2QA

-       The Royal Society for the Protection of Birds, 17 Regent Terrace, Edinburgh, EH7 5BN

-       The Nature Conservancy Council, North East (Scotland) Region, 17 Rubislaw Terrace, Aberdeen, AB1 1XE

– Mr P G Nairne and Mr M R Burt, CEGB, South West Region Headquarters, Bristol

– Mr A Robson, Environmental Studies, TP&R Division, CEGB, Generation Studio Branch, Laud House, 20 Newgate Street, London, EC1A 7AX

(See IEE Proceedings Volumne 30 Part A No 9 December 1983 – Environmental Aspects of Large Scale Wind Power Systems in the UK)

– Mr L A W Bedford, Building 156, Energy Technology Support Unit, AERE Harwell, Oxfordshire, OX11 0RA

2604EPEWGS01

Locations of measurements

Area likely to be affected by delayed image interference from the blades of a wind driven turbine generator on Burgar Hill
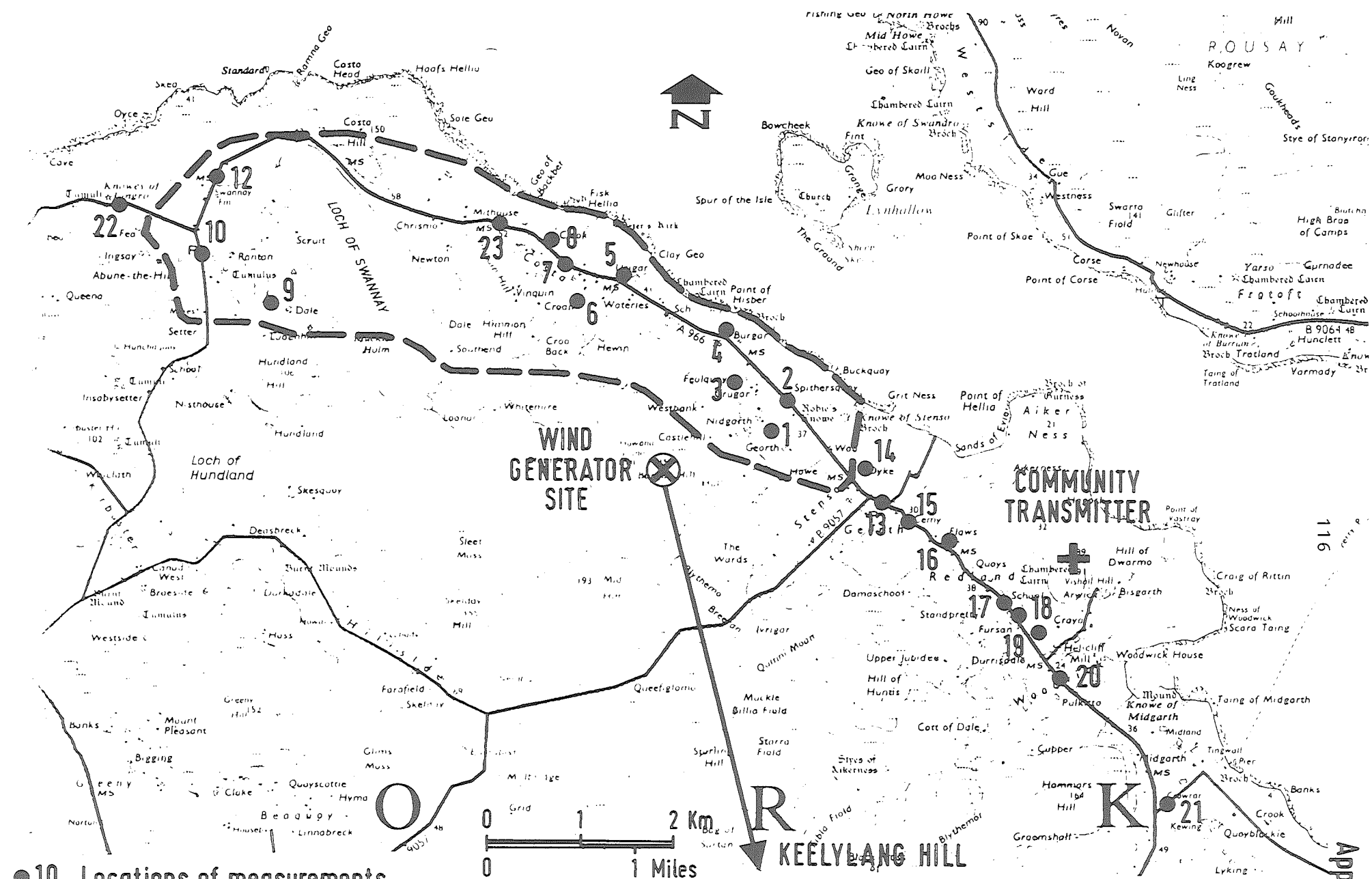
TEST RESULTS

TEST	NAME	LOCATION	LEVEL dB BBC1	BBC2	ITV	QUALITY	AERIAL
1	I CORRIGAL	EYIN HELGA EVIE	53	58	50	2	21+AMP
2	W HOURSTON	GRUGAR	49	46	43	2	45+AMP
3	LEECH	FEOLQUOY	48	**	40	1-2	45+AMP
4	STEVENSON	BURGAR	32	**	27	1	45+AMP
5	D ROLLAND	URIGAR	22	**	15	2	18
6	MATHEWS	QUARRYHOUSE COSTA	43	**	38	3	45+AMP
7	SPENCE	MUCKLE POW	42	**	41	3-4	45
8	HEDDLE	AIRSDALE	38	**	33	2-3	45 *
9	BRECK	BELMONT SWANNEY	48	**	48	3	10
10	ATKINSON	SWANNAY POST OFFICE	49	**	45	4	5
11	CTS/BT	SWANNAY POST OFFICE	44	**	44	4	CTS ***
	CTS/BT	SWANNAY POST OFFICE	49	**	49	3	CTS ****
12	SINCLAIR	MENOBRECK	52	**	57	4	45+AMP
13	RICHARDSON	DALE	42	41	43	2-3	18+AMP
14	HEATON	DYKE FARM	47	50	51	2	45+AMP
15	AIM 2 COUNCIL HOUSES		37	40	40	2	45+AMP
16	TAYLOR	FLAWS	58	61	61	3	45
17		EVIE SCHOOL	68	67	68	4	45+AMP
18	LUDGATE	NORTH WADES	48	52	50	4	8
19	CURSITER	HORAY EVIE	45	45	45	4	26
20	BALFOUR	WOODWICK STORES	69	63	64	3	
21		CRAWRAR AERIAL FAULTY					

*	BOUNCE FROM ROUSAY
**	BBC2 OFF AIR
***	BEST PICTURE
****	BEST SIGNAL

KEELYLANG HILL   625 LINE UHF COLOUR TELEVISION SERVICES

CHANNELS_____BBC 1 40, BBC 2 46, IBA 43, Fourth Programme 50
MAXIMUM EFFECTIVE RADIATED POWER (VISION)_____100 kW
POLARISATION_____Horizontal   RECEIVING AERIAL GROUP_____B
MEAN HEIGHT OF TRANSMITTING AERIAL_____165 Feet (50.3 m) agl,
NATIONAL GRID REF._____HY 378102   _____886 Feet (270.1 m) aod
TRANSMITTER SITE_____4 Miles West of KIRWALL, Orkney

ORKNEY
ISLANDS   Westray

Papa Westray   N. Ronaldsay

Sanday

BURGAR
HILL   Rousay   Eday

N

Stronsay

MAINLAND   Shapinsay

KEELYLANG HILL
UHF Transmitting
Station

0   5   10 Miles

0   5   10   15 Km

Hoy

S. Ronaldsay
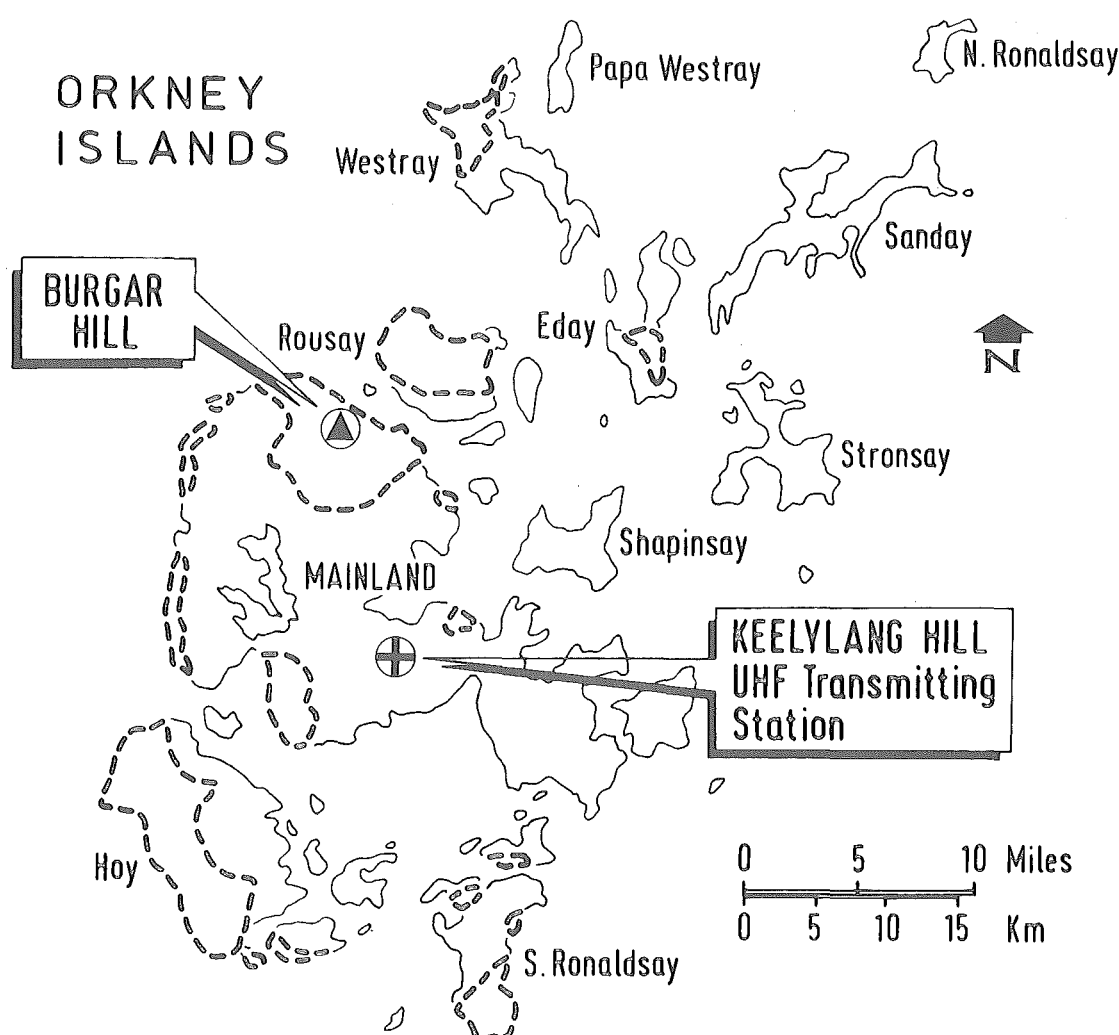
The expected service area is indicated by all areas shown above outwith the boundary ⚊ ⚊ ⚊
but the boundary should not be interpreted as a rigid limit.
For all services transmitted the areas covered will be similar, but there are bound to be
slight variations because of the different channels used.
The quality of reception on uhf can be very different at places which are only a short
distance apart and there will be, therefore, small pockets of poor reception which
cannot be shown.

APPENDIX 4

Field strength measurements and picture quality assessments

of the reception of Keelylang Hill before the construction

of wind turbine generators at Burgar Hill

EQUIPMENT

Aerial	:	Chelton log-periodic
Television receiver	:	National Panasonic TC48G (colour)
Measuring receiver	:	BBC Programmable Digital RC1M/508

RESULTS

Keelylang Hill (134.00)   Channels: 40(BBC-1), 46(BBC-2), 43(IBA)

No.	TEST LOCATION Name	FIELD STRENGTH/GRADE BBC-1	BBC-2	IBA	COMMENTS
1	Eyin Helga; Evie	39/2	–	38/2	Very weak picture. Images up to 30μ sec
2	Crugar	40/2	–	38/2	Very weak picture. Images up to 30μ sec
3	Feolquoy	51/2	–	53/2	Multiple images up to 40μ sec
4	Burgar	41/2	–	41/2	Weak picture. Images up to 40μ sec
5	Urigar	46/2	–	43/2	Multiple images up to 30μ sec
6	Quarryhouse, Costa	57/3	–	57/3	Grade 3 at 1μ sec. Other images not worse than Grade 4
7	Muckle Pow	62/4	–	62/4	Multiple images just perceptible
8	Airsdale	48/3-4	–	50/3-3	Multiple images
9	Belmont, Swannay	62/3	58/3	61/3	Multiple images up to 25μ sec
10	Swannay Post Office	67/2	62/2	66/2	Grade 2 at 30μ sec. Multiple images Grade 3
11	–				
12	Menobreck	57/3-4	54/3-4	56/3-4	Multiple images up to 30μ sec
13	Dale	51/2	–	49/2	Grade 2 at 5μ sec. Other images up to 30μ sec
14	Dyke Farm	53/2	–	53/2	Grade 2 at 5μ sec. Other images up to 30μ sec

No.	TEST LOCATION Name	FIELD STRENGTH/GRADE BBC-1	BBC-2	IBA	COMMENTS
15	No. 2 Council Houses	42/2	–	40/2	Grade 2 at 5μ sec. Other images up to 30μ sec
16	Flaws	51/2	–	48/2	Multiple images up to 25μ sec
17	Evie School	74/4	–	75/4	Multiple images just perceptible
18	North Wades	71/4	–	71/4	Multiple images just perceptible
19	Horay Evie	66/4	–	68/4	Worst image Grade 4 at 2μ sec
20	Woodwick Stores	56/2	48/2	48/2	Multiple images up to 30μ sec
21	Crawrar	89/4	82/4	88/4	Image at 2μ sec
22	Lingro	92/5	–	91/5	Good clean pictures
23	Mithouse	70/4	–	69/4	Multiple images just perceptible
	Burgar Hill site (measured 10m agl)	83/5	81/5	84/5	Good clean pictures
	predicted for heights above 35 m	94			

FIG.1

PROFILE – KEELYLANG HILL TO BURGAR HILL

Rousay

EYNHALLOW SOUND

Loch of Swannay

B

R.S.P.B.
OWNED

BURGAR
HILL

A

B 9057

A 966

Skelday Hill

Mid Hill

R.S.P.B.
LEASED

Starling
Hill

To KIRKWALL

A 986
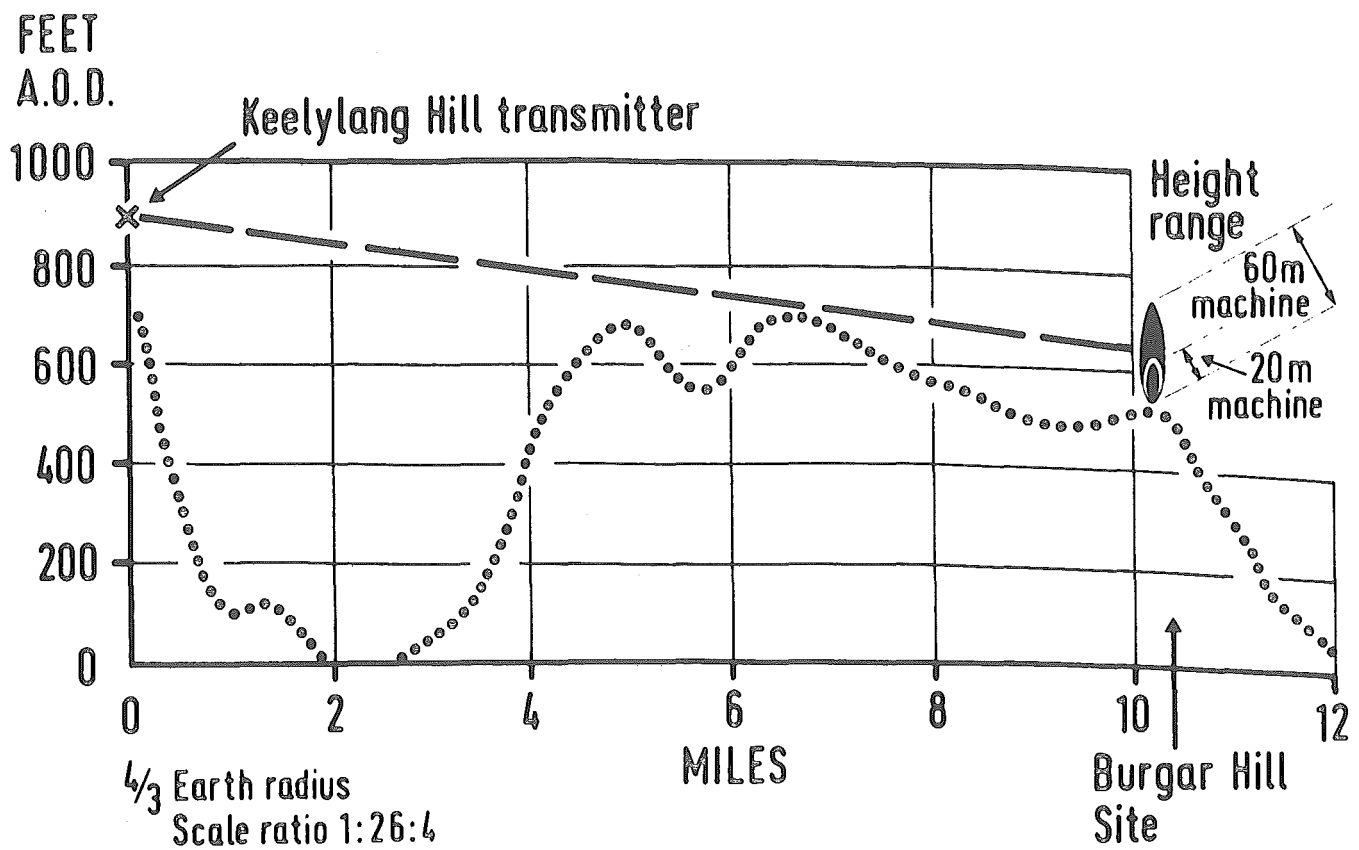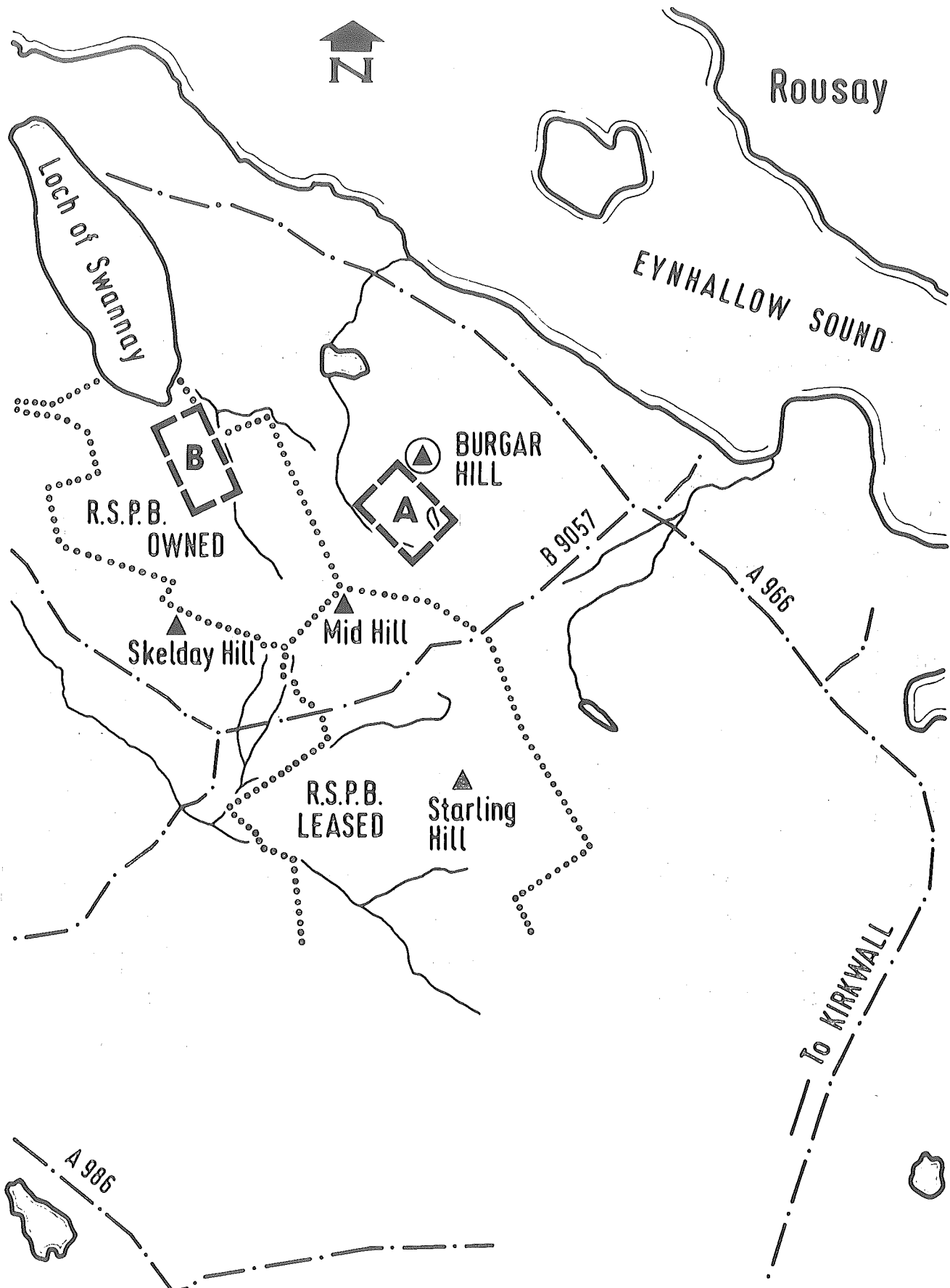
BURGAR HILL   CENSUS PLOTS FOR THE R.S.P.B.
SCALE : 1 / 50 000   BIRD MONITORING PROGRAMME
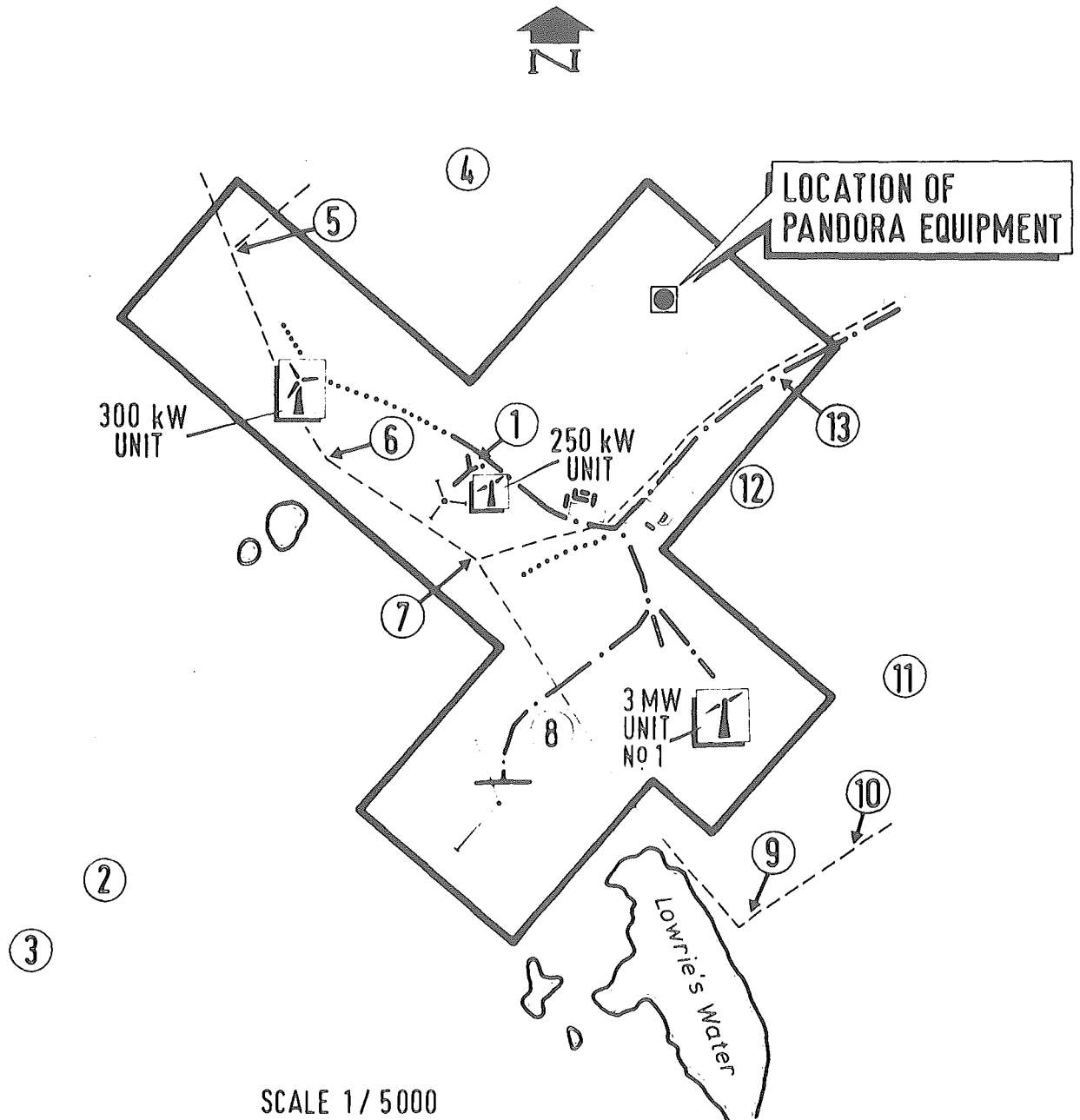
FIG.3

N

④

⑤

LOCATION OF
PANDORA EQUIPMENT

300 kW
UNIT

⑥

①

250 kW
UNIT

⑬

⑫

⑦

⑪

8

3 MW
UNIT
No 1

⑩

②

⑨

③

Lowrie's Water

SCALE 1/ 5000

BURGAR HILL
LOCATIONS FOR NOISE MEASUREMENTS

SCALE : 1/50 000

BURGAR HILL
LOCATIONS FOR NOISE MEASUREMENTS

FIG. 4

TABLE 1

NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD
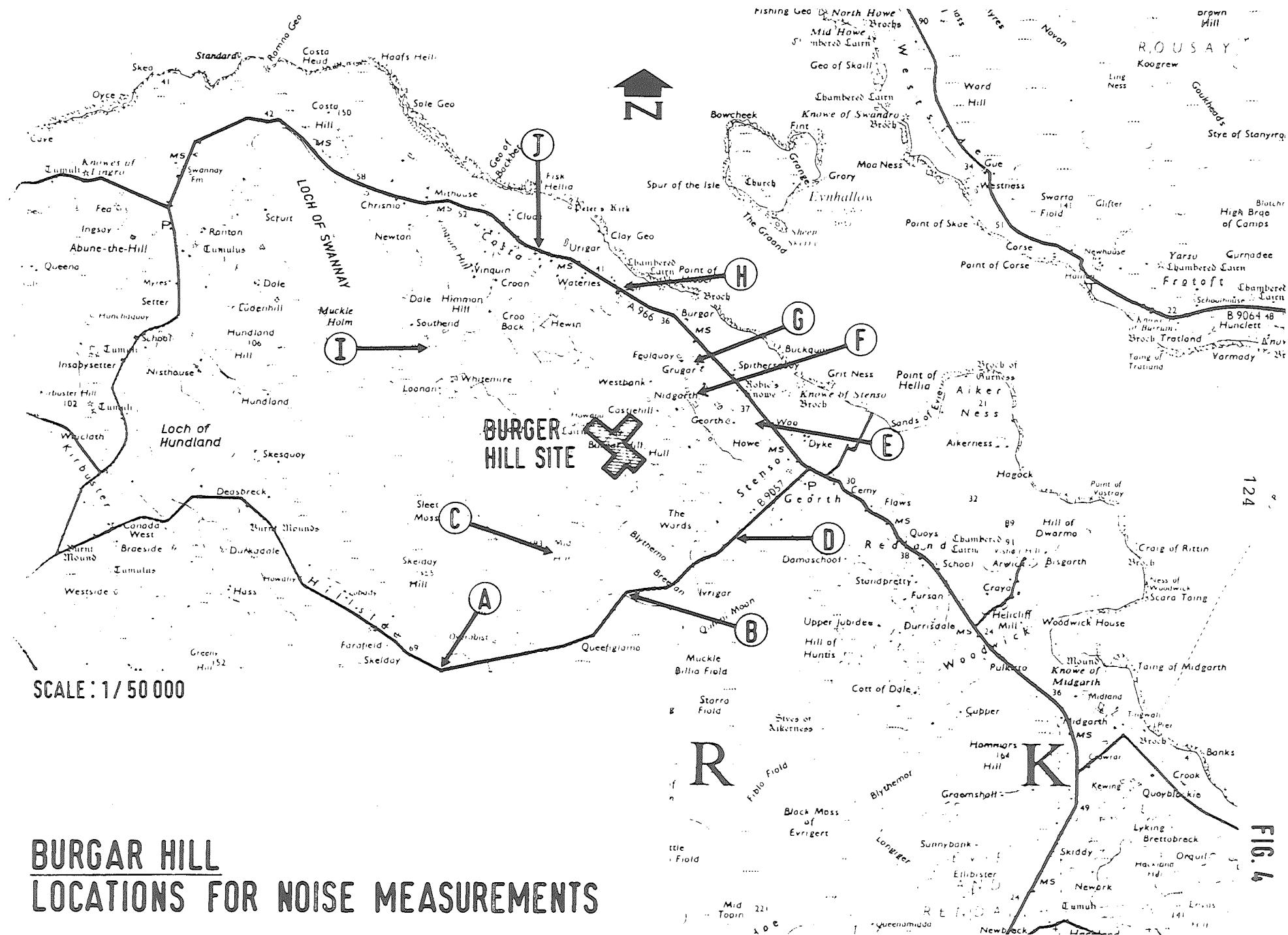
SOUND AND VIBRATION MEASUREMENTS

DATE: 16 September 1981

LOCATION: AT VARIOUS POSITIONS SURROUNDING BURGAR HILL

INSTRUMENTATION: B & K TYPE 2203 PRECISION SOUND LEVEL METER WITH TYPE 1613 OCTAVE FILTER

WEATHER CONDITIONS: OVERCAST WITH LIGHT SOUTHERLY WIND.   SEA VERY CALM APART FROM TIDAL RACE PAST EYNHALLOW

125

POSITION		TIME	WIND SPEED METRES /SEC	WEIGHTING		OCTAVE BAND ANALYSIS										GRID REFERENCE	
				LINEAR	"A"	31.5	63	125	250	500	1K	2K	4K	8K	16K		
A	AT JUNCTION OF B9057 WITH 'HILLSIDE' ROAD	1503	0.5	48	19	40	28	19	18	18	18	15	15	15	15	323	235
B	AT BEND IN B9057 ROAD	1517	1.5	45	22	30	30	26	21	15	15	17	15	-	-	344	244
C	AT TRIANGULATION PILLAR MID HILL SUMMIT	1535	variable 2.5	74	Min20 Max32	55-65	45	38	30	26	21	21	15	-	-	336	249
D	AT PASSING PLACE 50 METRES SW OF HOUSES	1557	2	45	26	40	30	28	19	20	20	18	17	17	-	356	250
E	AT ENTRANCE TO FIELD 25 METRES N OF WOO	1607	1	-	30	(Noise from nearby cattle)										360	263
F	PLOVERHALL FARM AT FOOT OF BURGAR HILL ACCESS ROAD	1615	2.5	(Excavator Dumping Bottoming Midway up Access Road to Burgar Hill) 64	31-40	45-54	50	50	26	26	28-38	20-26	19	15	-	352	263
G	AT ACCESS ROAD TO GRUGAR	1603	3	-	30	(Distant Chainsaw Clearly Audible)										354	270
H	AT SIDE ENTRANCE TO FORMER SCHOOL	1640	2	(Eynhallow Tidalrace clearly audible) 70	36	46	42	42	30	32	32	32	26	18	15	343	277
I	AT ROAD JUNCTION 600 METRES NNW OF WHITEMIRE	1650	2.5	66	21	42	34	26	26	18	16	17	15	17	-	322	271
J	BESIDE CHURCH AT COSTA	1700	2	60	Min30 Typical35	(Domestic Geese, seagulls and tidalrace audible) 40	36	27	25	24	27	20	17	18	-	334	282

TABLE 2

NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD

SOUND AND VIBRATION MEASUREMENTS

DATE: 17 September 1981

LOCATION: ON BURGAR HILL

INSTRUMENTATION: B&K TYPE 2203 PRECISION SOUND LEVEL METER WITH TYPE 1613 OCTAVE FILTER

WEATHER CONDITIONS: LIGHT SOUTHERLY WIND, CLEAR SKY AT FIRST CHANGING TO FULL CLOUD COVER BY COMPLETION OF TESTS

POSITION		TIME	WIND SPEED METRES /SEC	WEIGHTING		OCTAVE BAND ANALYSIS										GRID REFERENCE
				LINEAR	"A"	31.5	63	125	250	500	1K	2K	4K	8K	16K	
1	ON ROAD ISLAND ADJACENT TO 250 kW SITE	1412	6	86	38-44	70	58-66	52	42	40	42	30	28	28	28	
2	AT WHITE OVER YELLOW MARKER CANE 500 M SOUTH WEST OF POSITION 1															
3	AT WHITE OVER RED MARKER CANE 600 M SOUTH WEST OF POSITION 1															
4	AT EDGE OF BOGGY GROUND 240 M NORTH OF POSITION 1	1434	2.5	68-80	28	56	40-50	34-50	29	29	28	20	22	22	24	
5	AT JUNCTION OF FENCES	1500	3	72-80	28-34	40-50	39	32-48	28-34	23-30	20-30	20-30	20-30	20-30	15-25	
6	AT CHANGE OF DIRECTION OF FENCE LINE	1511	3	63-75	23	40-48	34	38	25	19-25	19-25	18	18	20	15-20	
7	AT GATE IN FENCE	1520	2	60-78	19	40-48	34	31	24	19	15	15	-	-	-	
8	ON ROAD ISLAND ADJACENT 80 M MET MAST	1539	2.5	55-65	20	44	38	30	20	17-20	17	15	-	-	-	
9	ON GATE ACROSS EXISTING TRACK	1605	1.5-2.5	70-80	20	50-60	45	30	25	20	20	20	-	-	-	
10	WHERE TRACK APPROACHES FENCE	1615	1.5-2	82	38-42	61	55	50	37	31	30-40	30	29	20	30	)Excavation)Works at
11	AT ROCKPILE ON EASTER EDGE OF BOG	1635	1.5-2	70-83	32	55	48	37	35	27	22	21	23	22	23	)Ploverhall)Farm End of
12	AT OVERHEAD LINE POLE NO 14 (2 POLES AWAY FROM H POLE)	1644	3	70	31-38	55	48	44	33	28	24	24	24	24	24	)The access)Road Audible
13	AT PASSING PLACE ADJACENT TO FENCE LINE CHANGE	1654	2	76	30-36	52	50	42	33	28	25	23	21	21	21	)at Positions)10 to 13

TABLE 2

NORTH OF SCOTLAND HYDRO-ELECTRIC BOARD

SOUND AND VIBRATION MEASUREMENTS

DATE: 16 September 1981

LOCATION: ON BURGAR HILL

INSTRUMENTATION: B&K TYPE 2203 PRECISION SOUND LEVEL METER WITH TYPE 1613 OCTAVE FILTER

127

WEATHER CONDITIONS: OVERCAST WITH LIGHT SOUTHERLY WIND. SLIGHT RAIN AT FIRST. HEAVY RAIN AT POSITION 3

POSI-TION		TIME	WIND SPEED METRES /SEC	WEIGHTING		OCTAVE BAND ANALYSIS										GRID REFERENCE
				LINEAR	"A"	31.5	63	125	250	500	1K	2K	4K	8K	16K	
1	ON ROAD ISLAND ADJACENT TO 250 kW SITE	1201	2-3	70	24	45	42	33	27	22	20	18	17	16	15	
2	AT WHITE OVER YELLOW MARKER CANE 500 M SOUTH WEST OF POSITION 1	1226	1	66	25	42	41	34	25	21	21	15	15	15	15	
3	AT WHITE OVER RED MARKER CANE 600 M SOUTH WEST OF POSITION 1	1239	1		25	No further tests. Rain water affecting microphone										
4	AT EDGE OF BOGGY GROUND 240 M NORTH OF POSITION 1															
5	AT JUNCTION OF FENCES															
6	AT CHANGE OF DIRECTION OF FENCE LINE															
7	AT GATE IN FENCE															
8	ON ROAD ISLAND ADJACENT 80 M MET MAST															
9	ON GATE ACROSS EXISTING TRACK															
10	WHERE TRACK APPROACHES FENCE															
11	AT ROCKPILE ON EASTER EDGE OF BOG															
12	AT OVERHEAD LINE POLE NO 14 (2 POLES AWAY FROM H POLE)															
13	AT PASSING PLACE ADJACENT TO FENCE LINE CHANGE															

Søren Rasmussen

National Agency for Physical Planning

— — — — — — —

SITING OF LARGE-SCALE WIND TURBINES IN DENMARK

Abstract

The site investigation of the Danish Wind Power Programme can
be regarded as consisting of three parts:

1. General siting investigations (1979-81).

Preconditions,method and results were published in may 1981,
(Store Vindmøller... vol 1 and 2). The main subjects were:

- mapping of wind conditions
- mapping and describing conflicting land-use interests
- survey of potential siting areas for siting models which are
  different in their respect to other land-use interests
- siting criteria (spec. distance from buildings) and their
  importance of how many turbines there may be sited in a
  certain area.

A hearing was arranged in which the County Councils and the
involved authorities were invited to comment on the methods and
results of the investigation,(vol.3).

2. Pilot projects for the siting of wind farms at Rødby and
    Brovst (1981-82).

The aim of these projects was to work out realistic siting pro-
posals in such a way that all local problems and reactions
might be identified. Thus an essential part of the work con-
sisted in investigating how the turbines could be sited with
most possible respect to landscape and recreative and agri-
cultural interest.

The alternative project proposals varied with regard to siting
configurations and turbine sizes and therefor also with the
number of turbines. Proposals for siting in geometric patterns

in connexion with dominant elements in the landscape as well
as in more dispersed configurations were drawn up and used in
discussions with local authorities and at public meetings (vol.4)

3. Pointing out sites for 500-800 wind turbines (present work).
The continuing siting investigation consists in going through
county by county,the best wind energy areas with a view to a
detailed assessment of their suitability for siting of turbines.
The areas are assessed and described,and siting proposals are
worked out.
On the basis of comments to each described area from the county
council and other authorities it shall be possible to receive
an impression of where to site the 800 turbines. Of certain in-
terest is to point out areas where the first 100-200 wind tur-
bines can be placed without conflicts with other land-use interests.

Siting of Large-Scale Wind Turbines in Denmark.

1. Introduction.

As part of the wind power programme sponsored by the Ministry of Energy and the Electric Utilities in Denmark, an investigation has been carried out by the National Agency for Physical Planning in the Ministry of the Environment with the purpose of mapping and selecting areas of Denmark estimated as suitable for the siting of large-scale electricity producing wind turbines - that is to say of the Nibe size and above.

This number of "News from the Wind Power Programme of the Ministry of Energy and the Electric Utilities in Denmark" gives a summary of the contents of four publications concerning the Danish siting investigation which up to now have been published. In connection with this is a short briefing on the work in progress.

The two first publications published in May 1981, dealt with the general investigation of the possibilities of siting a number of large wind turbines in Denmark corresponding to a yearly production of energy of 4 TWh. The first publication discusses methods and results, while the second describes the preconditions of the investigation.

The two latest publications in the series were published in the summer and autumn of 1982. Publication no. 3 contains the comments of various authorities and organizations on the general siting investigation. Publication no. 4 is a detailed description of two theoretical study projects concerning wind farms in respectively Rødby on the island of Lolland and Brovst in Northern Jutland.

As appears from the following section, the report "Wind Atlas for Denmark" which was published in August 1980, has been of considerable significance for the siting investigation, as it gives a method of assessing wind conditons and the basis for calculation of the energy production of the wind turbines.

2. General Siting Investigation

2.1. Mapping of Wind Conditions.

From the start of the investigation it became clear that a detailed mapping of wind conditions in Denmark was a prerequisite for the work in hand. Therefore a method - the wind atlas method - was worked out in collaboration with the Risø National Laboratory and the Danish Meteorological Institute after which the landscape was assessed and devided according to its surface roughness. This term can be defined as the quantity and character of wind-braking elements such as, for example, buildings and plantation. The assessment and mapping were carried out in cooperation with the County Councils.

This roughness classification was later altered to an energy classification, whereby the country was divided into four energy classes: A, B, C and D, with relative energy levels of respectively 100%, 75%, 55% and 32%. Related to the area of the country the four energy classes cover respectively 1%, 8%, 19% and 72% of Denmark. On the basis of this energy classification system, it has been possible to indicate location and size of the best areas regarding wind conditions in the various regions of the country.

2.2. Conflicting Land-Use Interests.

The actual work of investigation consisted after this in mapping and describing those interests with respect to open land which could be expected to conflict with the siting of wind turbines.

In this connection these land-use interests were devided into the following two groups:

Group 1.   Areas legally or economically secured for owner purposes (e.g. town zones, weekend-house areas, airports, bird-protection areas and military and preservation areas).

Group 2.   Areas in which regional or sector plans identify - but do not secure - interests in a particular kind of land-use (e.g. on the grounds of preservation considerations or agricultural or raw material interests).

As the choice between conflicting land-use interests depends on a political assessment, the siting investigation has only been able to outline the consequences this choice would have for siting prospects, if there are to be subtracted portions of the most suitable siting areas for other purposes.

In order to give some indication, the five following siting models were drawn up:

Model 1.   All the areas in the best energy classes (A, B and C).

Model 2.   Model 1 with the reduction of areas secured for other purposes (see map on page 4).

Model 3.   Model 2 with the reduction of areas covered by identified preservation interests.

Model 4.   Model 2 with the reduction of areas covered by identified raw material or agricultural interests.

Model 5.   Model 2 with the reduction of all identified interests.

The table on page 4 shows a county by county survey of the potential siting areas in the 3 best energy classes for each of the 5 siting models. The table shows among other things:

- that the best wind energy areas are to be found in connection with coastal regions, and that Western Jutland is particularly attractive because of its many open coastal areas.

- that in coastal areas there are often represented many other land-use interests, first and foremost preservation interests.

- that all areas in energy class A disappear if areas with identified preservation interests are omitted.

- that under the same precondition, only single areas in energy class B will be left in Western and Southern Jutland.

- that because of shelter-planting there are no areas of interest as regards wind energy in the interior of Jutland.

- that areas that possibly are omitted in consideration of agricultural interests - that is to say, the need for shelter-planting - primarily are to be found in Northern Jutland.

- that there will only remain areas in the next best energy class B, if all secured and identified land-use interests are to be respected, and these areas will not be in Western Jutland but around the Limfjord, in Eastern Jutland, on Western Zealand and on Lolland.

A summary and conclusion is given in section 2.5.

SITING MODEL 2

Areas in Energy class A and B
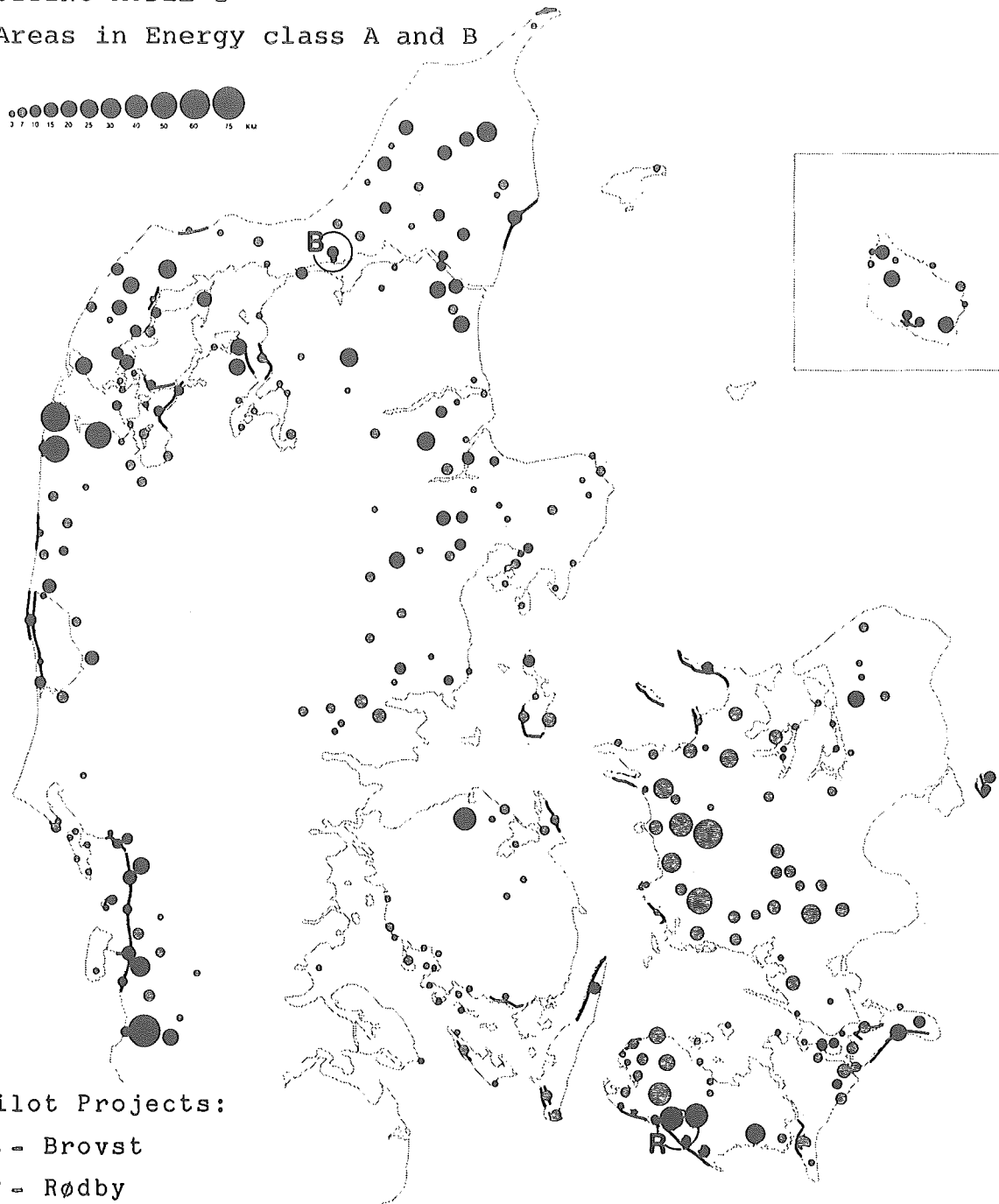
Pilot Projects:

B - Brovst

R - Rødby

DISTRIBUTION OF AREAS ON COUNTIES AND SITING MODELS

Siting model: Energyclass:	1			2			3			4			5		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
NORDJYLLAND	25	480	1615	2	365	1405	0	260	1200	0	140	—	0	80	—
VIBORG	35	365	865	5	275	755	0	110	430	2	225	650	0	115	420
ÅRHUS	20	285	1265	5	230	1170	0	145	885	5	220	985	0	100	815
RINGKØBING	75	445	275	25	310	245	0	115	190	20	245	180	0	110	125
VEJLE	0	95	430	0	70	370	0	55	285	0	70	360	0	55	280
RIBE	50	115	160	40	70	105	0	10	40	30	50	70	0	5	15
SØNDERJYLLAND	40	235	325	30	180	270	0	10	45	30	145	150	0	5	30
FYN	40	220	400	15	150	290	0	45	125	15	140	270	0	45	120
VESTSJÆLLAND	40	505	950	10	440	890	0	330	600	10	435	865	0	330	590
HOVEDSTADSOMRÅDET	10	110	555	5	70	420	0	40	300	5	70	410	0	35	295
STORSTRØM	65	550	1230	30	435	1065	0	195	655	25	430	1045	0	195	625
BORNHOLM	5	110	240	5	85	240	0	0	0	5	85	195	0	0	0
Total	405	3515	8310	172	2680	7225	0	1315	4755	147	2255	5180*	0	1075	3315*

Areas in km^2

2.3. Siting Criteria.

In order to be able to assess how many wind turbines can be placed in the areas in question - and with that, the amount of energy that can be produced - some criteria for siting must be defined. Among other things, distance from neighbouring buildings and the mutual distance between turbines must be established.

The necessity of maintaining a certain distance from neighbouring buildings is grounded in risks of acoustic noise, radio and TV interferences and the danger of broken turbine blades, which may be thrown several hundred metres on breakdown. As these conditions were not sufficiently known at the start of the project, pilot projects with varying distance criteria were carried out. Among other things it appeared that a 400 meter requirement would more or less preclude the siting of large-scale wind turbines in Danish agricultural areas.

In the general investigation, distances of respectively 200 and 300 meters from neighbouring buildings were used. This seems to be in reasonable accordance with the results and findings one at the moment can conclude from the preliminary investigations carried out concerning the influence of wind turbines on their surroundings.

By employing the siting criteria already established and drawing up proposals for siting of turbines in a number of selected test areas, it was possible to assess how many turbines may be placed in the different types of landscape and with that, in areas with differing energy levels.

In addition to the criterion of distance from neighbouring buildings, there was the requirement that turbines - in consideration of agricultural work - be placed along field and road boundaries, and that the preservation laws protection lines be observed.

Furthermore, the minimum distance between turbines was fixed at 7 rotor diametres in order to minimize the mutual wake effect between turbines.

2.4. Energy Production.

The investigation calculates with the two following turbine types:

> Type L: Hub height 50 m, rotor diameter 50 m and generator capacity 1 MW.

> Type S: Hub height 60 m, rotor diameter 80 m and generator capacity 2.5 MW.

With these two turbine types as a basis, the expected energy production for each siting model, if all areas were used for the siting of turbines, is specified.

Assuming the same annual production of energy of 4 TWh, two extremities can be mentioned. Large turbines (type S) with 200 metres to the nearest buildings and located in energy class A would involve an areal consumption of approximately 160 km^2, whereas small turbines (type L) with 300 metres to neighbouring buildings and located in energy class B would involve an areal consumption of approximately 1000 km^2. In the latter case the areal consumption is nearly 7 times as great as in the former one.

2.5. A summary of Publications 1 and 2.

In summing up, it can be concluded that the general siting investigation renders it possible to find sites for an assumed electricity production of 4 TWh per annum.

At the same time, it can be established that if all registered land-use interests are considered, no turbines can be sited more favourably than in energy class B, where they yield approximately 25% less energy than the best land-based turbines.

Therefore it is of decisive importance to investigate in more detail, whether some of the most favourable wind energy areas could actually be employed in the siting of wind turbines - despite the fact that they are covered by identified land-use interests. An elucidation of the potential land-use conflicts between the siting of large-scale turbines and preservation interests would be particularly momentous, as it is especially considerations of the latter kind that reduces the number of best suited areas.

Publication no. 1 calls attention to the fact that it has been necessary to draw up a number of provisional hypotheses, as many conditions concerning the impact of the turbines on the environment are not known - or insufficiently investigated. The publication thus points out the necessity of research into these conditions, if the siting possibilities are to be more precisely evaluated.

Among such supplementary research projects could be mentioned specific siting investigations that would reveal problems of a more local and practical nature, arising as a result of the siting of large-scale turbines in a particular area.

3. Comments on Publications 1 and 2 (Vol. 3).

In order to gain a more detailed impression of the potential problems in siting turbines in the areas mapped, a hearing was arranged in which the County Councils and the involved authorities and organizations were invited to comment upon the methods and results of the investigation.

The comments received contain many suggestions as to supplementary research concerning turbine siting. They stress in particular the need for an investigation of turbines sited offshore and also

a further investigation of the impact of large-scale turbines on landscape and bird-life.

On the whole, the comments are positive and appreciative of the general method used. At the same time they underline the fact that the provisional nature of the material has made more precise commentary difficult. Presumeably, this is the reason why none have made any independent efforts towards assessing certain areas as more suitable than others.

Several comments indicate that it was not made sufficiently clear that the 5 siting models are not placed in an order of precedence. Many have thus mistakenly interpreted model 5 as the result of the investigation.

The remarks in relation to the schematic employment of models point out the necessity of a more detailed explanation of the nuances of difference between secured and identified land-use interests. Elaborations of this kind will, of course, be made in the more specific siting study now in progress.

4. Windfarms at Rødby and Brovst (Vol. 4).

4.1. Pilot Projects.

Parallel with the hearing phase, detailed study projects (pilot projects) were carried out for the siting of turbines in two pre-chosen areas.

The aim of these projects was to work out realistic siting proposals in such a way that all local problems and reactions might be identified. Thus an essential part of the work consisted in investigating how the turbines could be sited with most possible respect to landscape and recreative and agricultural interests.

4.2. Choice of Area.

In selecting project areas, it was considered important that they should be different by way of both landscape and planning approach.

The Rødby area was chosen among the many large agricultural regions where buildings and plantations are so sparce that certain areas would be good potential sites for wind turbines. Agricultural interests are here given higher priority than environmental interests. Two sites were finally chosen: An inland area near Landø north of Rødby and a coastal area near Syltholm immediately east of Rødby harbour. Both sites are in energy class B. However, the coastal site is somewhat better than the inland one.

The Brovst area is representative of the many open regions of fjords and meadows, especially found in Northern and Western Jutland. It is characteristic of these regions that environmental interests are usually predominant. Towards the south, the area borders the Limfjord. The sites within a limit of 500 m from the

coastline are thus in energy class A, while the remaining area is in the best part of energy class B.

4.3. Working Method.

In each area, a working group consisting of local politicians and technicians was established. The groups discussed preconditions, working procedures and project proposals - all of which was drafted in the wind energy secretariat of the Agency for Physical Planning.

It was decisively emphasized that potential sites as well as the alternative project proposals be visualized, so the people involved had a reasonable chance of assessing the consequences with respect to landscape and siting strategy. For this reason, a method was developed by which it was possible to draw the turbines and 'double-expose' them onto slides of the landscapes in question.

The alternative project proposals varied with regard to siting configurations and turbine sizes and therefore also with the number of turbines. Proposals for siting in geometric patterns in connexion with dominant elements in the landscape as well as in more dispersed configurations were drawn up.

The local electric utilities worked out schemes for the grid-connection of the turbines. Underground cables were used in both areas. Electrical diagrams and prices are reproduced in the report.

The final study projects were delivered for a political assessment in the municipalities and County Councils. They were also sent to local landowners and interest organizations. In addition to this, the projects were presented and discussed at public meetings.

4.4. The Rødby Project.

On the basis of the schematic proposals drawn up, the working group decided that the project should employ fewer but larger turbines (type S) and that it was more important to place turbines along field boundaries than to erect them in particular geometric patterns.

Following this, 19 turbines divided into 3 groups were sited in the Landø area. This division into smaller groups made it possible to site turbines in the open agricultural areas between the buildings connected to roads. It was proposed to erect 7 turbines near Syltholm parallel with the coastline immediately behind the dike, see figure 1.

The energy production per turbine in the Landø area is estimated at 6,5 - 7 GWh per annum while a turbine near Syltholm is estimated at 7 - 7,5 GWh per annum, because it is closer to the coast. The total energy production of the two areas is judged to be 180 GWh per annum.
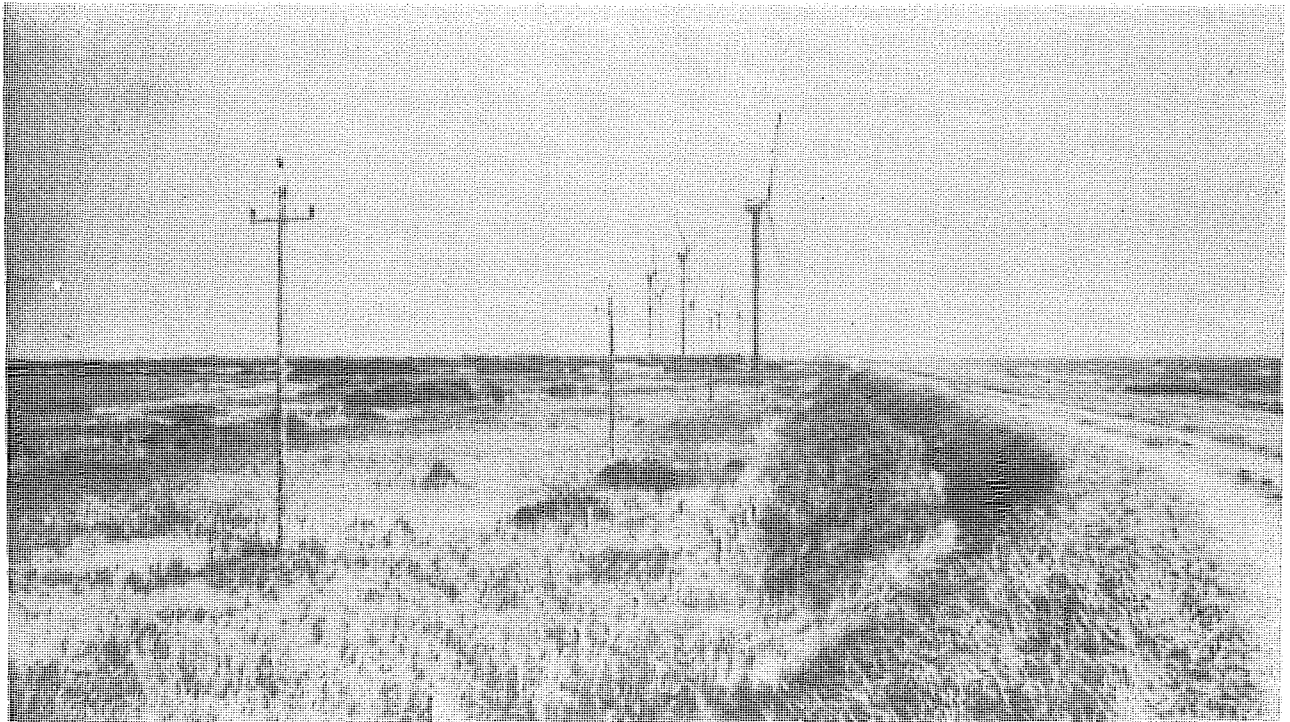
Figure 1. Wind turbines at Rødby (photo collage).

4.5. The Brovst Project.

The larger turbine type was also preferred in Brovst. By siting fewer but larger turbines near the coast, the land behind could be left free and from a certain distance it was possible to perceive the cluster of turbines as a single unit in the open neutral landscape. The working group placed landscape and aesthetic considerations high on the list of priorities, and thus the turbines were positioned in a tight, easily recognized pattern in two rows parallel with the coast.

The siting proposal includes 15 turbines of which 11 can be seen in figure 2. In order to avoid the mutual wake effect between the turbines, they were positioned with a mutual distance of 5 rotor diametres (400 m) as a minimum. In this way, the windfarm covers in all an area of 3 times 0,5 km to which must be added access roads. In consideration of the special character of the area, it was proposed to grid-
connect the turbines through underground cables.

As the area nearest to the coast is a bird-protection area, and a wish was expressed to place the turbines by canals and at field boundaries, it was not possible to site them nearer than 500 m to the coast. This reduces the energy production by some few per cent. The total energy production of the 15 turbines is judged to, be approximately 120 GWh per annum.
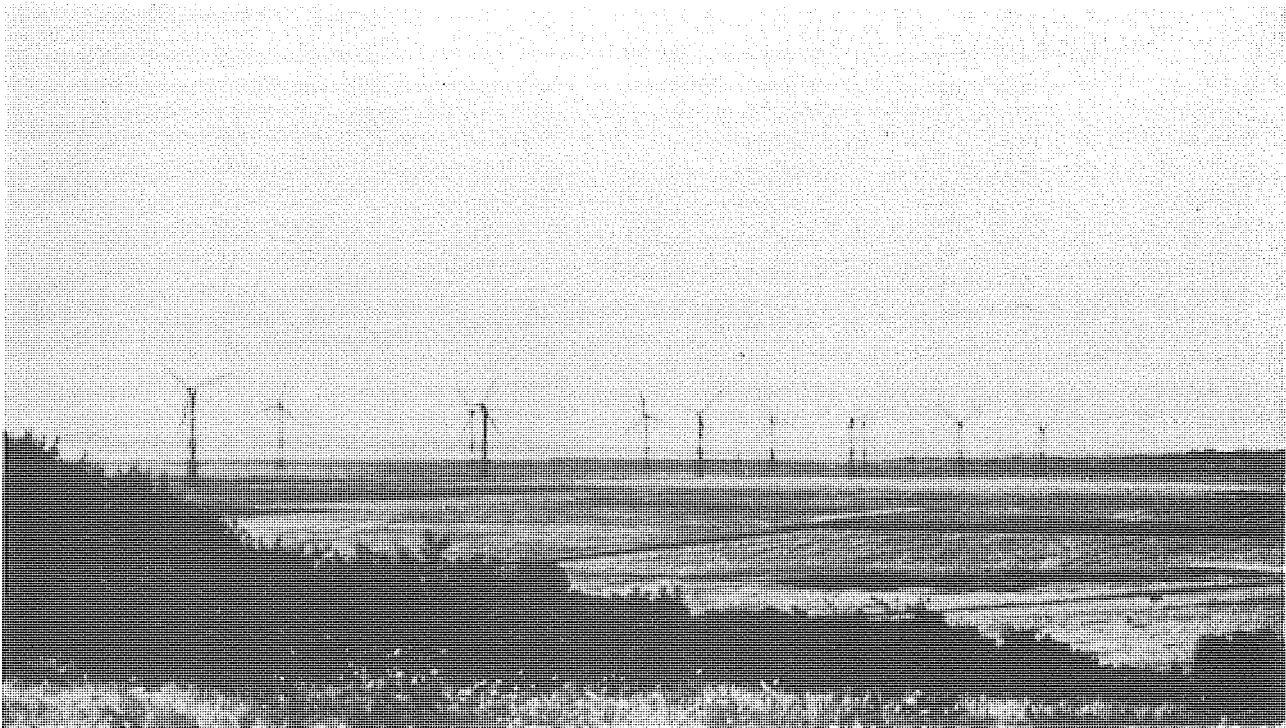
Figure 2. Wind turbines at Brovst (photo collage).

4.6. Experience.

Both projects have given useful experience in landscaping pro-
blems. It can thus be established that the size of the turbines
and their mutual distance mean that the siting proposals must be
exceedingly simple in order to appear harmonious set in the
Danish landscape and, moreover, that the siting of turbines in
connexion with elements such as roads or canals achieve only a
poor landscaping effect, as these cannot be recognized at a
distance.

Experience has also shown that groups of large turbines, such as
discussed here, must be placed at a considerable distance from
one another in order not to 'melt' together visually. On the
other hand, a good visual effect can be attained if the distance
between single turbines in a group can be reduced.

In summing up, it can be concluded that general rules for the
siting of turbines cannot be established. Planning work must be
carried out for each individual area taking the local landscape
and environment into account.

4.7. The Hearing Phase.

Although the projects were pure study projects, the munici-
palities and County Councils have carried out realistic assess-
ments.

The municipalities of Rødby and Brovst have formally approved and recommended the projects. The County Councils of the particular areas have not made any formal decision. Instead, they have described the planning work the realization of the projects would incur, and they have also brought forth the preliminary assessments of their various planning departments. The statements of the municipalities and County Councils as well as comments received from local organizations are appended to the report.

The project proposals were presented at public meetings in Rødby and Brovst. Both meetings were well attended and there was an enthusiastic question and discussion round. Many had views on turbine siting. Others wished first of all to have a thorough knowledge of the general economic and energy supply conditions before making any decision on projects of this kind.

Both opponents and supporters of the turbine projects expressed satisfaction with the many slide-illustrations that made a visual understanding possible.

5. Present Work.

The continuing siting investigation consists in going through, County by County, the best wind energy areas with a view to a detailed assessment of their suitability for siting of turbines.

Areas that in publication no. 1 are contained within siting model 2 are used as a basis. The best of these areas are assessed and described, and the number of turbines that can advantageously be sited in each area is assessed on the basis of siting proposals.

The siting problems in relation to the selected areas are discussed with the technical departments of the County Councils, as it is a difficult task to clarify to which extent it is to be expected that the individual areas can be used for large-scale turbines, because other land-use interests might be placed higher on the list of precedences.

The planning of open land areas is a County Council task, but the Councils have had difficulties in deciding to which degree they should let themselves be involved with planning work as regards siting of wind turbines, because the political, economic and technical preconditions for wind power on a major scale have still to be finalized. It seems however, that the co-operation between the Agency for Physical Planning and the County Councils has been established on a basis, which permits the siting investigation to be carried through according to the above mentioned aim.

The assessment of the most favourable potential areas for wind turbine siting is largely concluded for the whole country. At present the draft proposals have been presented to and discussed with the County Councils. Provided their comments, including lists of precedence of areas of interest, are available at mid-1984, a final and detailed report on land-based wind power will be published later this year.

The overall aim of the work is to point out sites for 500-800 large-scale wind turbines (2.5 MW), whereby the total wind energy production should correspond to approximately 10 per cent of the total expected electricity consumption in 1995. A preliminary aim is to point out suitable sites for the first 100-200 wind turbines in the best wind energy areas - that is to say energy class A and the best part of energy class B.

As it is of decisive importance to turbine economy that the sites for additional turbines should be as favourable as possible, separate negotiations are being carried out with the National Agency for the Protection of Nature and Sites and the Ministry of Defence on the chances of involving certain parts of the bird-protection areas and military training areas for turbine siting.

Furthermore, an investigation of the possibility of offshore siting of large-scale turbines has been initiated in cooperation with the Ministry of Public Works. The basis of this investigation is the recently completed technical and economic investigation of offshore wind power in Denmark. (DEFU, EEV 83-01, March, 1983). An English translation of this offshore report is in preparation.

The offshore siting investigation follows a normal hearing strategy according to which the involved authorities are asked to comment on the tabled proposals. Answers from all authorities have recently been received, and this information will now be studied and evaluated keeping in mind that a final report with detailed offshore siting proposals should be ready for publication at mid-1984.
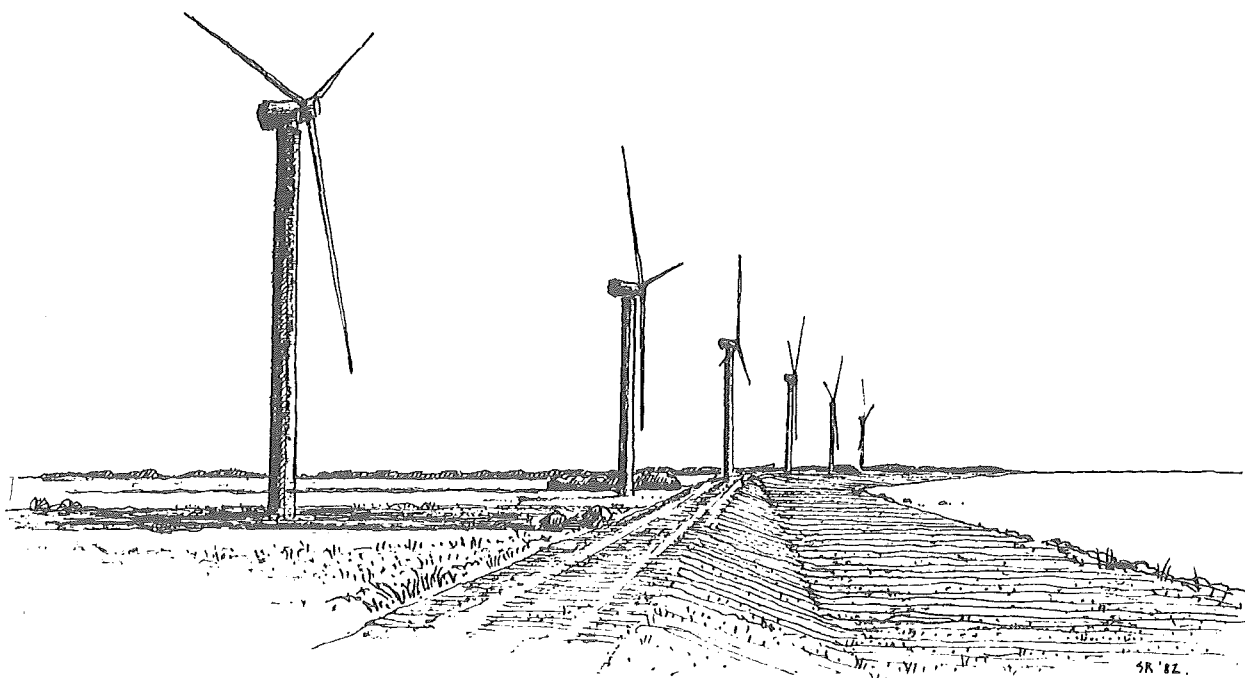
STATUS MAY 1984 AND DESCRIPTION OF RELATED INVESTIGATIONS

Status pr. 1. may 1984

Up till now the whole country has been traversed and detailed assessed
- except from two counties of minor interest.

For all areas of interest, there is made a description containing
informations about:
 - the character and utilization of the landscape
 - the existing planning considerations
 - considerations on the exploitation of windenergy

As regards the last-mentioned point it is necessary to work out a
draft showing the maximum number of turbines that can be placed in
an area as well as drafts showing more realistic proposals. Furthermore
it is important to calculate the possible amount af energy that can
be produced in the different proposals. As a basis for these proposals
there has been worked out maps where the distances to neighbouring
buildings are marked. Distances at 2oo meters to single farmhouses
and 3oo meters to villages have been used.

The descriptions mentioned above and belonging detailed maps are sent
to the County Councils together with a map of the whole county where
the areas of interest for siting large turbines are shown.

Thereafter meetings are arranged with technicians from the County
Councils and the material is presented and discussed.

The purpose of this contact is to get a technical (i.e. not political)
evaluation of the possibilities for applying the proposed areas.

Two of the County Councils have delivered their comment in writing
and two have for the present given verbal answers. Unfortunately
it has been proved that it is very difficult to get the promised
assessments from the County Councils. Some have not answered even
after a year, but now the comments seem to come in.

Temporary experiences

On account of these comments and the discussions with the remaining
County Councils it is possible to give a very preliminary summary
of the experiences from the present work:

- It seems to be possible to find sites for the first loo turbines
  in the western part of DK (west of the Great Belt)
- On the other hand it can be difficult to point out sites enough
  for a loo turbines in the eastern part of DK.

- It can be expected that the remaining 4oo-6oo turbines will have
  to be placed in areas with a lower energylevel in the wind, whereby
  the cost of producing 1 kWh will be comparable with that of an
  offshore sited turbine.
- It has been possible for the County Councils to comment on the
  localization of the loo-2oo turbines in the preliminary aim, but
- obviously the County Councils cannot foresee to assess the sites
  of the following 4oo-6oo turbines.
- They have pointed out that one shall not underestimate the local
  reactions from municipalities and owners of a plot of land, and
- they have difficulty in making a realistic technical valuation
  of the material as long as the questions of the energypolicy
  are so open.

These temporary experiences now seems to prove a need for political
considerations for the exploitation of windenergy.

It is to be hoped that a report dealing with more concret possibilitie
of siting a number of large wind turbines i DK can constitute a basis
for such considerations. (The report is expected to be published
spring 1985 by the National Agency for Physical Planning).

In connection with the siting investigation other separate studies
have been made. A status for these is given:

Birds and wind turbines

This investigation is just fullfilled and a report is published
(by Vildtbiologisk Station, Kaløe, 84lo Rønde)

The aim has been to illustrate any conflict between wind turbines
and birds.

On behalf of observations at the large turbines at Nibe and Koldby
and in other areas of interest for future siting, the questions of
the scaring effect on birds, the risk of collision and the changes
in the environment have been studied.

The report concludes:
- that a direct scaring effect on birds only was observed a few times
- that there have not been found any birds killed by collision
- that human disturbance in connection with the installations may
  be a disturbing element for the birds
- that it has not been possible immediately to state any change in
  the environment in connection with the installations

Siting in international (Ramsar- and EEC-) birdprotection areas

The National Agency for the Protection of Nature and Sites has assessed
the possibilities for siting large wind turbines in certain border-
districts of the birdprotection areas. The answer is positive, and
the Agency has pointed out 5 areas of interest for exploitation of
vindenergy, where the birdprotection interest are so reduced that
turbines not are expected to be in conflict with the birds.

Untill now this assessment only include the eastern part of DK, the
western part is to follow.

Turbine siting in military training areas

The Ministry of Defence has now assessed the possibilities for siting
large windturbines in certain military training areas. The ministry
has answered, that except from a couple of small areas of less inter-
est for siting, it will not be possible to site turbines in the
training areas.

Off shore Siting

The recieved comments from authorities show that there are several interrests at see, that might be in conflict with off shore turbines. Most important are the fishing and navigation, but also preservation interests are represented off shore.

Because of this - surprising - conclusion, it has been necessary to ask the authorities to give more detailed informations. A final report should be ready at the end of this year.

Contact for the Siting Investigation:

Søren Rasmussen & Claus Lewinsky
The National Agency for Physical Planning
1o. kontor
Holbergsgade 23
DK 1o57 København K
Danmark

Special Questions of Siting

of Wind Turbine Arrays and

Networks

by

H. Ernst, L. Henke

(Lahmeyer International)

(1)   Introduction

As part of a study /1/ sponsored by the Federal Ministry
for Research and Technology the realistic siting potential
for large wind energy converters (WEC) for the northern
flatlands and the highlands of the Federal Republic of
Germany has been analyzed. The investigation has been
restricted to areas of sufficiently good wind energy
potential comprising a total land area of 56,000   square km
and offshore of 39,000 square km.

In this contribution the results on the number of land-based
WEC's of the GROWIAN type in the FRG will be presented as a
function of restricting and excluding criteria (see also the
contribution to the IEA expert meeting in 1982 /2/).

(2)   Influence of different safety distances in different topo-
graphical regions

The standard set of safety distances together with the
standard spacing (1000 m) of groups of WEC's results in
a total of 7000 sites. The effect of a stepwise reduction
of the safety distances within different typical regions
- coast, far off coast, highlands - is reflected in Fig. 1.
Less stringent safety distances will increase the siting
potential, at most in the coastal areas and least in the
highlands. In total, about 50% of the reference siting
potential can be gained by cutting down the safety distance
range from 1000-250m to 500-250m. In terms of wind energy
potential the effect would even be higher because of the
great significance of the coastal areas.

(3)   Influence of standard spacing of WEC-groups on siting
potential

In areas of scenic beauty or in natural or recreational
parks, large WEC's must not be excluded, but the impact of

WEC's may be reduced to acceptable levels by increasing the standard spacing of the WEC's.

Fig. 2 and Fig. 3 show the reduction of the siting potential based on a standard spacing of 1000 m (Variant A) for 3 other sets of spacing distances in the case of the North German flatlands resp. the German highlands.

Because the highlands are generally areas of scenic beauty, natural parks and recreational areas, they are strongly (91%) affected by restrictions on the spacing of WEC's, whereas the flatlands are affected up to a maximum of 35% of its standard siting potential. Thus, in the interest of the utilization of wind energy, it is very important to find a compromise between different utilizations.

(4) Excluded siting potential due to conflicting use

In contrast to the areas of scenic beauty and to natural and recreational parks, there exist other areas, where WEC's have to be excluded due to conflicting use of higher priority. Examples of such areas are the following:
- shallows
- bird sanctuaries
- tourist areas
- low level flight areas
- national parks
- military installations
- airports,etc.

From Fig. 4 it can be seen that especially in the region of excellent wind energy potential, more than 50% of the total potential have actually been excluded. In areas

classified as medium (Class 2), the relative exclusion is much less but still amounts to more than 1300 sites. For the whole of the Federal Republic of Germany, about 3300 sites had to be excluded because of conflicting use in areas of excellent or good wind conditions in comparison to the remaining (not excluded) 1637 sites.

Summarizing one can state that the definition of safety distances as well as of spacing of WEC's in areas of alternative use and the definition of areas of conflicting use play a dominant role in establishing a realistic siting potential for WEC's. The results may serve as a basis for establishing criteria to be applied in the process of future decision-making regarding the large-scale use of wind energy in the Federal Republic of Germany.

/1/ BMFT-Research project: "Darstellung realistischer Regionen für die Errichtung insbesondere große Windenergieanlagen in der Bundesrepublik Deutschland" Lahmeyer International GmbH, Frankfurt, to be published in 1984.

/2/ Henke, Realistic siting of LS/WECS in Germany, Jül-Spez-100, Kernforschungsanlage Jülich, 1981.

DISTANCE (M)	STANDARD	VAR. I	VAR. II
TO VILLAGES, CITIES	1000	750	500
TO HOUSES/ GROUPS OF HOUSES	500	400	300
TO MAIN ROADS/ RAIL ROADS/ROUTES OF SEA TRAFFIC	500	400	300
TO HIGHVOLTAGE TRANSMISSION LINES	500	400	300
TO SIDE ROADS	250	250	250

COASTAL AREA:	NO. OF SITES[1]	%	NO. OF SITES[1]	%	NO. OF SITES	%
REPRES. AREA (KARRHARDE)	29	100	46	138	50	172
TOTAL AREA	2975	100	4107	138	5118	172

AREA FAR OFF COAST						
REPRES. AREA (BREDDORF)	60	100	75	125	87	145
TOTAL AREA	662	100	828	125	960	145

HIGHLANDS						
REPRES. AREA (ROTHAARGEBIRGE)	53	100	61	115	70	132
TOTAL AREA	3362	100	3866	115	4437	132

| TOTAL | 7000 | - | 8801 | - | 10515 | - |

1) DISTANCE OF WEC = 1000 M

INFLUENCE OF VARYING SAFETY-DISTANCES IN DIFFERENT TOPOGRAPHICAL REGIONS	Abb. 1

VARIANTS OF RESTRICTIONS

TYPES OF AREAS AND ITS FRACTION IN %	%	A	B	C	D	FRACTION POLITICALLY DISPONIBLE $\frac{A-D}{A}$ [%]
		STANDARD DISTANCES (M)				
SCENIC BEAUTY	13	1000	3000	6000	∞ 1)	
NATURAL PARK	3	1000	2500	5000	∞ 1)	
RECREATION	19	1000	2000	4000	∞ 1)	
OTHER 3)	65	1000	1000	1000	1000	
CLASS OF WIND SPEED — 1		104	57 2)	48 2)	32	69%
CLASS OF WIND SPEED — 2		854	710 2)	684 2)	635	26%
CLASS OF WIND SPEED — 3		2680	2035 2)	1919 2)	1696	37%
ALL CLASSES		3638	2802	2651	2363	35%

1) ∞ $\hat{=}$ NO UTILIZATION BY WEC

2) NUMBERS INTERPOLATED

3) AREAS WITHOUT RESTRICTION

CLASS OF WIND SPEED

1: $>$ 10 M/S

2: $\geq$ 8.5 M/S

3: $\geq$ 7.5 M/S

NUMBER OF CONVERTERS IN NORTH GERMAN FLAT LANDS DEPENDING ON VARYING RESTRICTIONS	Abb. 2

VARIANTS OF RESTRICTIONS

TYPES OF AREAS AND ITS FRACTION IN %	%	A	B	C	D	FRACTION POLITICALLY DISPONIBLE $\frac{A-D}{A}$ [%]
		STANDARD DISTANCES (M)				
SCENIC BEAUTY	64	1000	3000	6000	∞ 1)	
NATURAL PARK	I	1000	2500	5000	∞ 1)	
RECREATION	26	1000	2000	4000	∞ 1)	
OTHER 3)	9	1000	1000	1000	1000	
CLASS OF WIND SPEED	I	41	9 2)	4 2)	0	100%
	2	638	140 2)	62 2)	0	100%
	3	2683	825 2)	535 2)	303	89%
ALL CLASSES		3362	974	601	303	91%

1) $\infty \overset{\wedge}{=}$ NO UTILIZATION BY WEC

2) NUMBERS INTERPOLATED

CLASS OF   I: EXCELLENT WIND POTENTIAL

WIND SPEED   2:   GOOD   "   "

           3:   SATISFACTORY "   "

NUMBER OF CONVERTERS IN GERMAN HIGHLANDS DEPENDING ON VARYING RESTRICTIONS	Abb. 3

| | CLASS OF WIND SPEED | | I+2 |
	I	2	
NORTH GERMAN COASTAL AREAS			
SHALLOWS			
BIRD SANCTUARIES	1525	572	2097
TOURIST AREAS	(1470%)	(67%)	(219%)
UNRESTRICTED SITES	104	854	958
	(100%)	(100%)	(100%)
HIGHLANDS			
LOW LEVEL FLIGHT	125	632	757
NATIONAL PARK	231	68	299
TOURIST AREAS	88	-	88
MILITARY INSTALLATION, AIRPORTS	4	22	26
ARMY TRAINING AREA	8	28	34
	456	750	1204
	(1112%)	(117%)	(177%)
UNRESTRICTED SITES	41	638	679
	(100%)	(100%)	(100%)
BRD:			
EXCLUDED WEC	1981	1322	3301
NOT EXCLUDED WEC	145	1492	1637

NUMBER OF CONVERTERS WHICH ARE OR ARE NOT EXLUDED DUE TO CONFLICTING USE	Abb. 4

Environmental aspects of the Netherlands windfarm project
by J.A. Kuipers
N.V. KEMA, the Netherlands

Summary

It is one of the main objectives of the windfarm project to
study the influence of environmental aspects.

Although in principle a safe life design shall be pursued, it
is one of the site selection criteria that there should be no
dwellings inside the windfarm or at a certain distance of it.

Nevertheless, problems arise as to noise emission of
windturbines as well as to establishing background levels at
higher wind velocities. They are being investigated thoroughly.

It results from rough measurements that TV interference seems
to be less severe than was expected.

Acceptance of a windfarm by people living nearby at a distance
of about 300 to 400 m or in villages at a distance of 1000 m is
one of the study aims, as is the acceptance by visitors and
society as a whole.

The experiences with license procedures for the windfarm
demonstrated how the conflict with farming can be minimized.

Besides the above subjects, studies of fauna, flora, bird life
and shadow inconvenience will be coordinated under supervision
of a special committee.

Safety issues, noise, T.V. interference, visual impact and
impact on farming will be discussed more in detail.

Introduction

Although one of the main objectives of the windfarm project is
defined as: "Gaining experience with licensing procedures and
environmental aspects", the preparatory studies and activities
have been advanced so far, that the impact of some
environmental aspects has become more obvious [1].
Fig. 1 shows that the study aims of environmental aspects are
considerable when compared with studies of technical subjects.
This was judged to be necessary as the global experiences with
windturbines in the 100 to 1000-kW range are scarce and for the
Netherlands can be neglected. The experiences to be gained with
300-kW windturbines in a fairly large pilot windpower plant
(5.4 MW) possibly combined with one MW windturbine (fig. 2) are
considered to be indispensable for the utilization of wind
energy on a larger scale.
During the site selection of the windfarm project, besides
technical criteria, a considerable amount of environmental
criteria were used (fig. 3).
The following chapters will discuss safety issues, noise, TV
interference, visual impact and impact on farming and the
coordination of all the study aims on environmental aspects in
the Netherlands.

Safety issues

A site selection criterion for the windfarm project was the
possibility of an arbitrarily chosen safety distance of 250
meters around the windturbines (fig. 4).
This safety distance is based on an international literature
study on blade failures and noise emissions from windturbines.
Houses or farm houses are not allowed inside the windfarm area
and within the safety distance; this is to limit the risk of
people being hit by a blade fragment and to limit the noise
annoyance to local people.

The probability of throwing an object is considered to be very low, as show calculations from the 25-m HAT at the Petten test field in the Netherlands. This 300-kW windturbine is located near roads and a restaurant inside the test field.

Glazed frost chipping off windturbine blades have not observed in the Netherlands climate so far.

Although in 1983 a commercial 300-kW windturbine in the southern part of the country failed due to overspeed of the rotor [2], the blades remained attached to the hub (fig. 5).

As the windfarm will be situated partially in pasture land and partially in arable land (fig. 6), despite the safety distance, it appears to be necessary to draft safe life designs for the windturbines to avoid any risk of danger to farmers and cattle inside the windfarm area.

This means that the windturbines will not be designed by rules but the mechanical and fatigue calculations will be based on a "design philosophy by analysis" the principles of which are given in the ASME codes for a life period of at least 20 years.

Besides: - fatigue tests on a rotor blade will be carried out,
 - fail safe constructions used,
 - quality assurance will be applied during the design period, manufacture and assembly,
 - vibration detectors on the main shaft will be installed and
 - a tight inspection schedule will be observed.

We think this to be a better method to limit risks and to avoid limitations to the siting of windturbines instead of developing and verifying further analysis methods of thrown blades or throw calculations.

This argument has also convinced the local people during hearings, knowing that the best technical means will be employed to avoid any risk of blade failure.

Noise

The conclusions from consulted international literature
concerning noise emission of windturbines can be summarised as
follows [3-12]:
- Windturbines may but need not cause noise annoyance to nearby
  houses or villages, though there are no admissible noise
  criteria combined with variable background noise due to wind
  velocities.
- Noise measurement methods and measurement apparatus are not
  standardised for windturbine noise.
- The noise problems with upwind turbines seem to be less
  severe than with downwind turbines.
- If noise problems are distinguished beforehand, the following
  measures seem to be possible to reduce the noise level:
  . Increase the distance to the nearest houses
  . Reduce the noise from machinery in the nacelle with noise
    reduction measures
  . Re-design the shape of the rotor blades to decrease the
    blade wake noise.
- The blade noise appears to depend mainly on rotor speed.
- The background noise level increases with higher wind
  velocities,
- Well-designed windturbines need not to be audible at a
  distance of more than 200 m.

An inventory of noise emission levels for Dutch commercial
small and medium-scale windturbines (15 to 60 kW and 300 kW
respectively) gave results as given in fig. 7.
For reasons of comparison, the noise level of the upwind MOD-2
(2.5 MW) in the USA and of a 10-MW windfarm with 300-kW
windturbines of Dutch manufacturers are also given.
When these noise levels are compared with a 40-dB contour line,
around the windturbine or around a 10-MW windfarm, which seems
to be a reasonable average noise criteria during nighttime, the
following conclusions can be drawn:
- small-scale windturbines (about 20 kW) demonstrate an
  acceptable noise level at a distance of about 100 m.

- Medium-sized windturbines (about 300 kW) compared with 15 x
  20 kW windturbines emit by about 5 to 10 dB more noise and
  compared with the 40-dB contour line 10 to 15 dB too much
  noise at a distance of 300 to 200 m.
- The distance of the MOD-2 windturbine compared with 100 x
  20-kW windturbines seems to be reasonable at about 700 m, but
  appears now to be about 2000 m.
- There is a difference in distance of a 10-MW windfarm
  equipped with MOD-2 or 300-kW Dutch windturbines (on the one
  side) compared with 500 x 20-kW windturbines (on the other
  side).
- Finally it may be concluded that there is a certain need to
  reduce the noise emission levels of single medium-sized
  windturbines, but it is undoubtedly required for
  Megawatt-scale windturbines or MW-scale windfarms to decrease
  the noise emission of today's windturbines.

This is also shown by fig. 8 with a windfarm of 24 x 300-kW
windturbines surrounded by a 40-dB contour line which is
calculated from the measured single windturbine noise levels.
In comparison to the safety distance of 250 m around the
windfarm it is obvious that noise attenuation measures are
necessary to have the 40-dB contour line comply with the safety
distance criterion.

In the above inventory of noise emission levels there seems to
be a slight tendency that a three-bladed (lower rpm) 300-kW
windturbine is preferred to a two-bladed (higher rpm) 300-kW
windturbine, though the measurement results are still very
poor. Both types of windturbine are variable-speed machines.
Further investigations on this subject will be made.

Further study of the windturbine noise sources by using special
antennas (see annex) from the Netherlands Institute of Applied
Physics (TNO-TH), has revealed that the noise from the
machinery in the nacelle of both 300-kW windturbine types dealt
with dominates the noise from the blades or blade wakes (fig. 9).

The machinery noise will be subject to detailed investigation, while a literature study demonstrated that attention must be paid to the shape of the trailing edge and tip of the blades to decrease blade or blade wake noise. It is expected that the noise emission of the nacelle will decrease significantly. Concerning the low-frequency noise/infrasound from the MOD-1 downwind turbine, we have the feeling that natural frequencies from the windturbine construction may also be a reason for this because of focusing of the noise by the rotor blades. The question is if more attention should be paid to the noise emission from the source instead of that what can be heard by the observer at a certain distance, a relation could be established between the natural frequencies of the MOD-1 construction and this typical noise phenomenon. If this problem could be examined and solved, it would be no longer necessary to over-emphasize the low-frequency problem. Regarding noise regulations for large-scale windturbines it seems interesting to know:

- At which height is the wind regime representative of the noise immision on the ground at a certain distance from the windturbine?
- At which height on the ground and at which distance should windturbine noise be measured?

The national regulating authorities in the Netherlands are convinced already that existing regulations must be supplemented for background wind noise. They initiated a study supervised by a special committee of how the background noise level varies with wind velocities at different typical locations such as:

- No obstacles like trees or houses
- Only trees or only houses
- A combination of trees and house(s).

As far as regulations for low frequencies are concerned, it is interesting to know with which apparatus they shall be measured and which criteria are admissible.

Initiatives for serious and extensive noise measurements on
different types of machines within the IEA community should be
accomplished in special expert meetings or in a working group.
With the improvement and development of measuring techniques
especially for background noise levels, interesting results are
achieved in the Netherlands.
Validation of theoretical prediction tools depending on design
parameters and technical development to minimize noise emission
of windturbines can only be achieved with the cooperation with
the industry. The question is which difficulties can arise when
the results are published officially.

TV interference

During site selection of the windfarm the conclusions were
taken into account of an inventory report by the Dr. Neher
Laboratory of the Netherlands PTT. The report deals with the
possible effects of and restrictions on large-scale WECS's,
from the telecommunication systems applied in the Netherlands [13
In the report the following telecommunication services are
considered:
- Fixed services
- Broadcasting services
- Mobile services
Particular attention is paid to the requirements relative to
interference bases on the scattering theory. On the siting of
WECS the following restrictions were taken into consideration:
- WECS cannot be installed within an area, bounded by a
  distance of 100 meter from the centre line of a fixed service
  link.
- The minimum distance between the WECS and the transmitting
  antenna of a broadcasting service has to be 6 km.
- Limitations are imposed on the height of obstacles in certain
  regions surrounding the antenna of the fixed satellite
  service at Burum.
For further conclusions with respect to the siting of WECS,
several recommendations are given in the above report, such as
to study the influence of rotating blades on the impact of
Pulse Amplitude Modulation caused by WECS on the quality of
broadcasting and mobile services.

Finally it has been concluded that after the recommended
investigations it seems possible to select sites for a windmill
network which does not affect telecommunication networks.
Based on experiences with the disturbances of television
reception due to reflections by high-tension overhead lines,
some calculations are made by KEMA for a windfarm with 24
medium-sized (300-kW) windturbines.
The provisional conclusions are that complaints can be expected
depending on the frequencies at distances from about 1000 to
4000 m. But from rough measurements it seems that these
calculations of the influence of the rotor blades is too
pessimistic when the rotor blades are in the horizontal
position (horizontal polarization of TV signal). This shall be
studied further.
Rotating of the rotor blades introduces a periodic blinking on
the TV screen.
Therefore the limiting threshold for the interference of a
windturbine with rotating blades is lower than that of a static
object of the same size.
We do not have enough indications to state that any particular
design or blade material causes less disturbances than others.
We have the intention to study this further.
Cable TV and special local slave transmitters are not the only
solutions because the use of a directional receiving antenna is
also possible. Besides cable TV is usually found in areas with
high density of population, while WECS will be situated in
low-density areas where cable TV is not available.
The cost of cable TV for such areas would be excessive.
Finally it would appear that the management of cable TV should
be put out to contract.

Visual impact

The "visual pollution" caused by the windfarm project has been
discussed also during hearings with the local people,
particularly in the windy flat area where there are very few
obstacles.
In the preparatory phase of this project it was judged to be
necessary and important to show the local people the visual
impact by the windfarm on its surroundings by using
true-to-nature artist impressions.
Pictures were taken from the existing landscape at several view
points and distances. After that the windfarm was drawn in the
same pictures with the lay-out as shown before (fig. 2).
Although the judgement of visual pollution is personal, there
is a difference in looking at "a forest of windmills" depending
on the point of view and the accessory distance (see fig.
10-17).
One important feature seems to be the shape of the windturbines
e.g. the ratio of the diameter(s) to the height of the tower.
Therefore, in the tender specification it has been prescribed
that there should be no differences in tower diameters but that
one diameter or a tapered tower design should be offered.
In this pilot windfarm project the distances between the
turbines in a row are chosen 5 x the rotor diameter and between
the rows 8 x the rotor diameter for study reasons only (fig.
18). Future large-scale windfarms should preferably be chosen
haphazardly depending on existing roads, ditches or allotments
of farming land, as was the case with the typical old Dutch
windmills for centuries. By doing so, the conflict with the
environment can be minimized, as can the impact of the
direction sensitivity of the windfarm on the energy production.
The question whether from a visual viewpoint a small number of
large windturbines is more acceptable than many small units,
cannot be answered before the results of public acceptance and
perception of the pilot windfarm project are known.

Impact on farming

During the site selection procedure it was noticed that at the finally chosen site a land consolidation programme was in progress. Consultations with the representative committee of landowners lead to an acceptable solution for the infrastructure for both parties.

The Dutch Electricity Generating Board (SEP) will obtain three strips of land to install the rows of windturbines and to lay out roads and cable trays between the windturbines.

The roads will be bordered by ditches to drain the land and to keep the cattle at the grass. Permanent fences are therefore not or hardly necessary.

The remaining land between the ditches will be partially pasture land and partially used for cultivation of various crops. The roads may be used also by the farmers increasing the accessibility while the efficiency of the land will be increased by a drainage system.

The net land required for windturbines, roads and cable trays is about 20% of the total windfarm area with a surface of about 550,000 m^2, fig. 19 and fig. 20.

The remarkable coincidence of searching a spot for a windfarm and a land consolidation project shows how after carefully negotiations a conflict with farming can be minimised and how farming interest enable a windfarm to be installed. However, this positive attitude could not be noticed for other sites during the selection period, especially not for sites without pasture land or land cultivated after expensive land reclamation activities.

Coordination of study aims

Besides the above subjects, the study of fauna, flora, bird life and shadow inconvenience will be coordinated and supervised by a special committee (AMMA). The study aims of this committee also concerns:
- The public acceptance and perception of the windfarm by local people, travellers and visitors.
- The impact on farming.
- The visual impact of the windfarm on the surroundings by using special pictures and a film of a windfarm model
- Analyses of the landscape when windfarms, windturbines on lines, single windturbines or small clusters of windturbines should be applied on a larger scale in the future.

All these activities and several others will be coordinated by highly qualified specialists who are on the committee such as:
. Physical planners
. Environmental/natural philosophers
. Agriculturists
. Psychologists and sociologists

The funds necessary for the windfarm project will be supplied equally by the Ministry of Economic Affairs and by SEP being the owner and operator of the windfarm after commissioning.
At the request of SEP a project team of KEMA's Engineering and consulting department will execute the technical engineering activities in coordination with the national wind energy programme according to the organisation diagram as given in fig. 21.

Time schedule

Site preparation can be started in May 1984.
Pre-operational studies (bird life), as references for future
investigations, have been started.
Pre-operational wind measurements can be started in July 1984.
The windfarm will be ready for operation in the middle of 1986.
The study of the visual impact of the windfarm has been started
using a model.

Acknowledgement

Literature

[1]   The Netherlands Windfarm Project
        D.J. Bornebroek and J.A. Kuipers
        N.V. KEMA, The Netherlands
        Published at the I.E.E. Conference 3-6 April 1984

[2]   Investigation reveals cause of PEP-2 Machine failure
        N.V. Provincial Energy Company of Zeeland
        Distributed at the I.E.E. Conference 3-6 April 1984

[3]   Environmental impact of wind energy utilization
        Bent Sorensen
        Tekst nr. 34, 1980

[4]   MOD-2 Wind-Turbine System Cluster
        Research Test Program
        Volume 1 - Initial Plan
        Larry H. Gordon, March 1982

[5]   The environmental effects of wind turbines
        by P.T. Manning, May 1982

[6]   Final Report: Windenergy
        Evaluation for the C.E.C.
        by Dr. Peter Musgrove, Reading England, November 1982

[7]   Evaluation of the Potential Environmental effects of
        wind energy system development
        Interim final report
        August 1976

[8]   Fourth International Symposium on Wind Energy systems,
        September 21-24 1982. Swedish WTG's.
        The noise problem by S. Soderquist

[9]   GE MOD-1 noise study
        R.I. Welss

[10]   Enhancement of far-field sound levels by refractive
         focussing
         Dennis W. Thomson and S. David Roth

[11]   Predictions of low-frequency and impulsive sound
         radiation from horizontal-axis wind turbines
         Rudolph Martinez, Sheila E. Widnall, and Wesly L.
         Harris

[12]   The NASA-LeRC Wind turbie sound prediction code
         Larry A. Viterna

[13]   An inventory of conditions and requirements for the
         installation of large scale windmill networks with
         respect to their impact on telecommunication networks
         Report 454 TM
         by J.M.G.A. Ouderling and J.T.A. Neessen
         Netherlands P.T.T.

STUDY AIMS

DETERMINATION OF ENERGY PRODUCTION IN DIFFERENT WIND CONDITIONS

STUDY OF THE EFFECTS OF MUTUAL PARALLEL OPERATION AND PARALLEL OPERATION WITH THE PUBLIC GRID

STUDY OF HARMONIC DISTORTION

STUDY OF THE INFLUENCE OF WAKE EFFECTS ON ENERGY PRODUCTION AND ON MECHANICAL STRESSES IN THE CONSTRUCTION

SOCIAL ACCEPTANCE BY THE PEOPLE

INFLUENCE ON AGRICULTURE AND LAND CULTIVATION

NOISE PRODUCTION

INTERFERENCE WITH RADIO AND TELEVISION _I ⁻ɪ'ALS

INTERACTION OF·BIRDS AND WINDTURBINES

FIG. 1

FIG. 2

170

LAY OUT WINDFARM

|| ROAD
●   WINDTURBINE 300 KW.
✕   TOWER, WINDMEASUREMENTS
▮   BUILDINGS
C   CLUSTER
C3   OPERATION CENTRE
●   WINDTURBINE 1 A 3 MM.
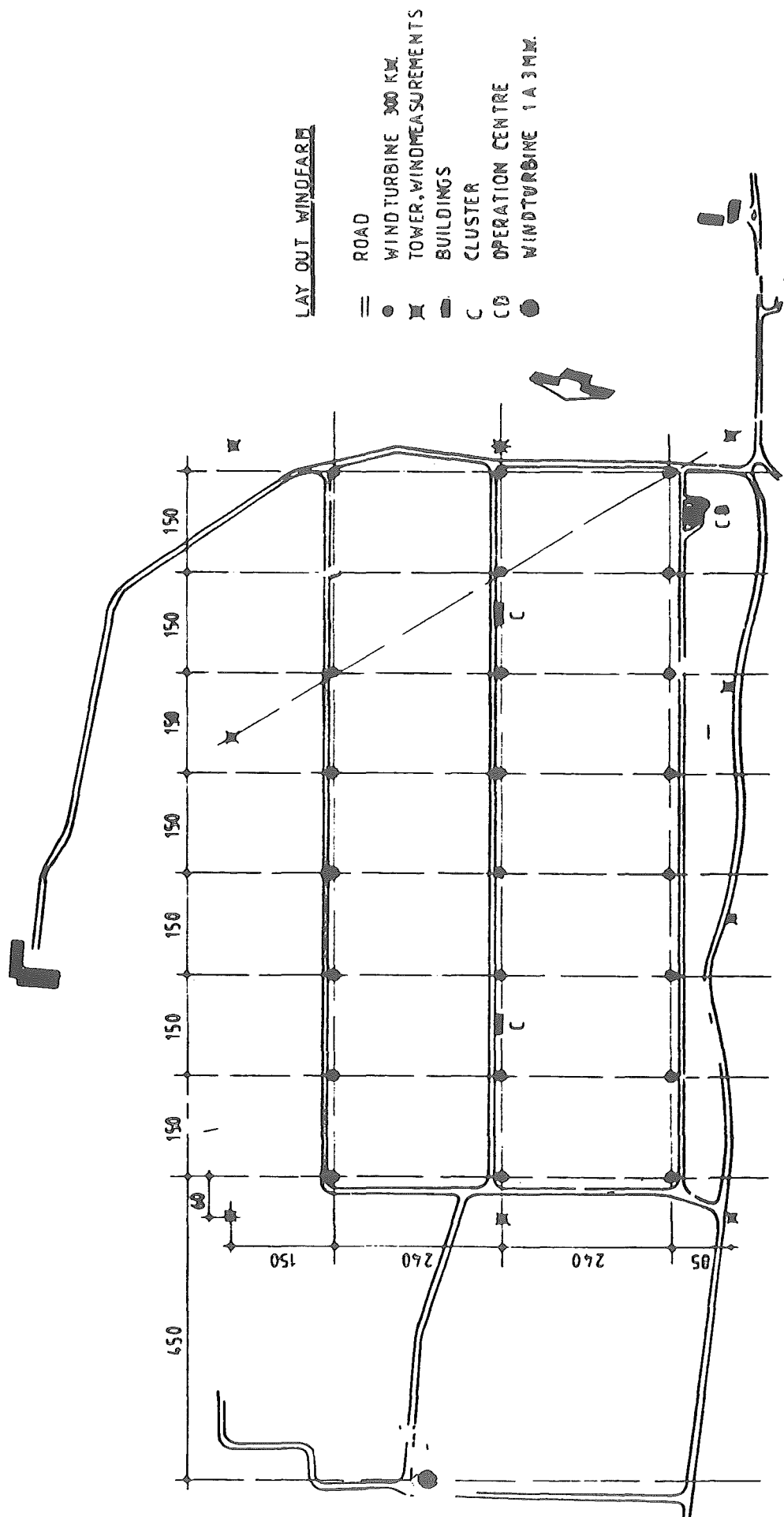
SITE SELECTION CRITERIA

ANNUAL AVERAGE WIND VELOCITY 6.5 $^m/_{sec}$ AT A HEIGHT OF 40 m ABOVE GROUND LEVEL

ROUGHNESS OF THE SURFACE 0.05 - 0.03 m

INFRASTRUCTURE OF THE SITE AND SURROUNDINGS

SOIL STRUCTURE

ACCESSIBILITY OF THE SITE

CONNECTION POSSIBILITIES TO THE HIGH-VOLTAGE GRID

AGRICULTURE

BIRD RESEARCH POSSIBILITIES

INCONVENIENCE FOR PEOPLE LIVING IN THE NEIGHBOURHOOD

LANDSCAPE

GOVERNMENTAL POLICY

FIG. 3

LAY-OUT WINDFARM WITH SAFETY DIST NCE

A

FIG. 4

172

FIG. 5

* = LW ∿ 10 log W
or LW ∿ 10 log N

CAPACITY
WINDFARM

ROUGH
DISTANCE
TO 40 dB(A)
CONTOUR

MOD-2

STATUS
DUTCH
WINDTURB.

dB(A)   120

110

LWR(A)
A-WEIGHT
NOISE
CAPACITY
LEVEL

100

90

—2000

—700   m

—250

CRITERIA
ACCORDING
EXISTING
REGULATIONS

—100

10   100   1000 kW   10 MW

ELECTRICAL CAPACITY ⟶
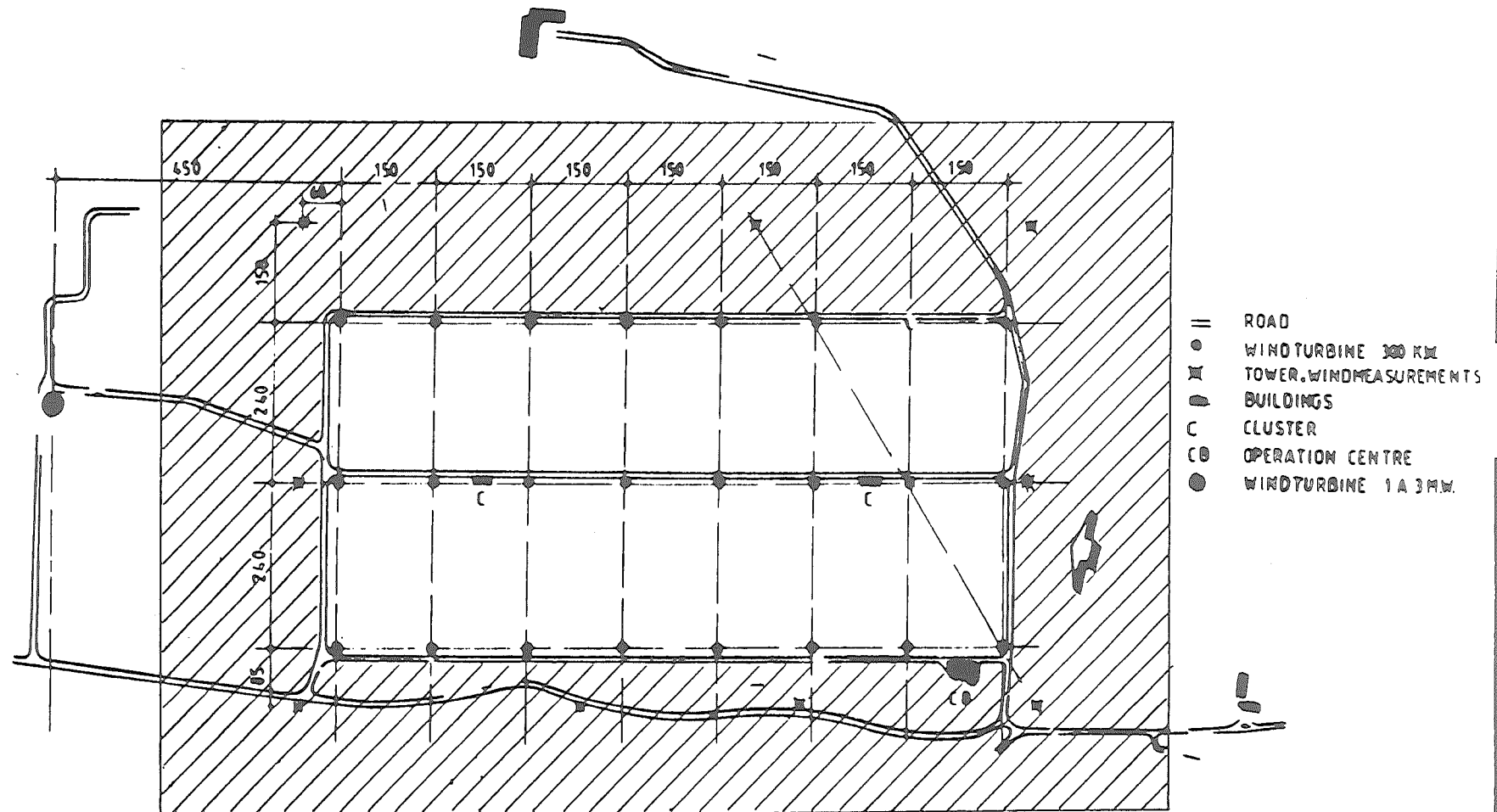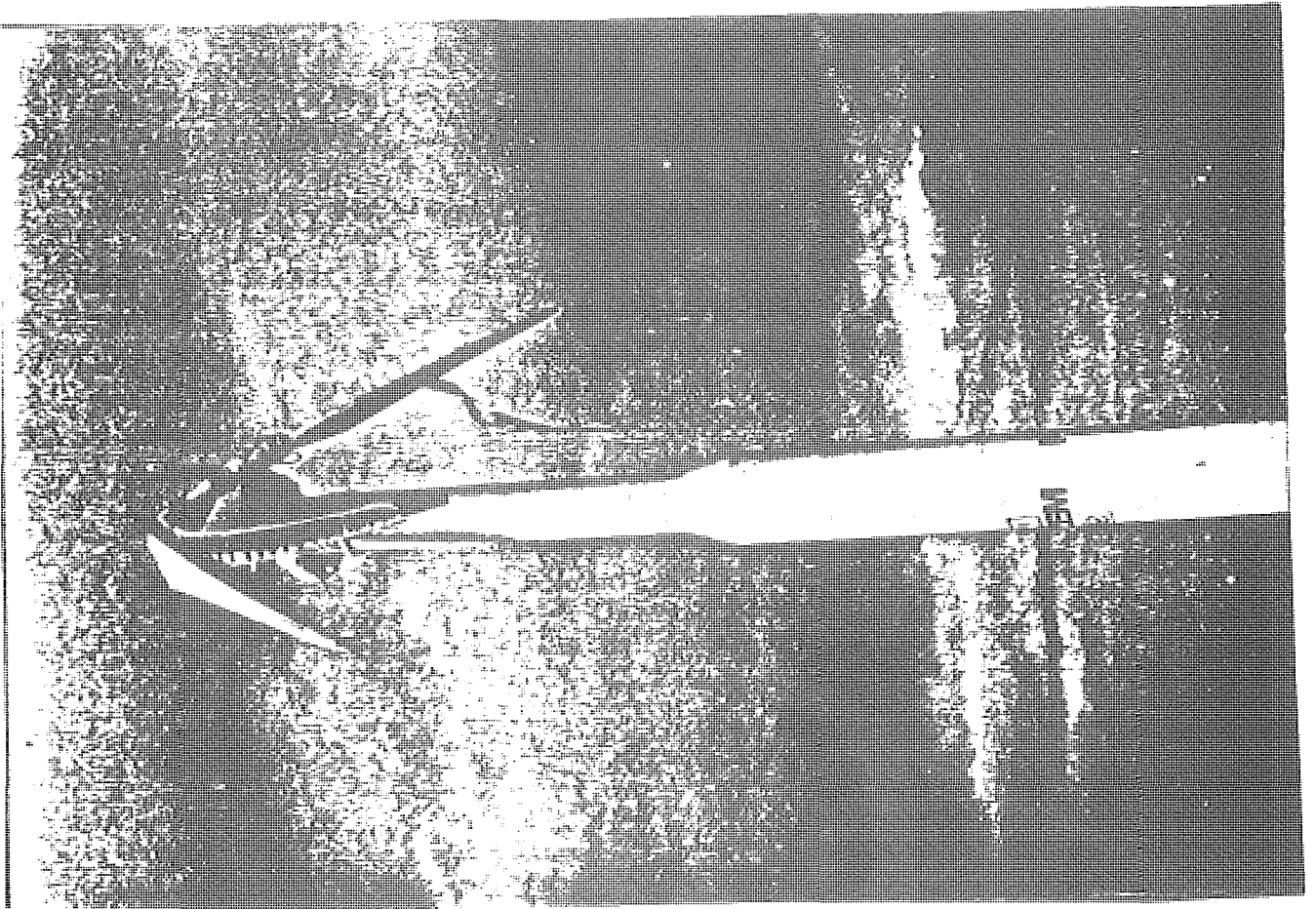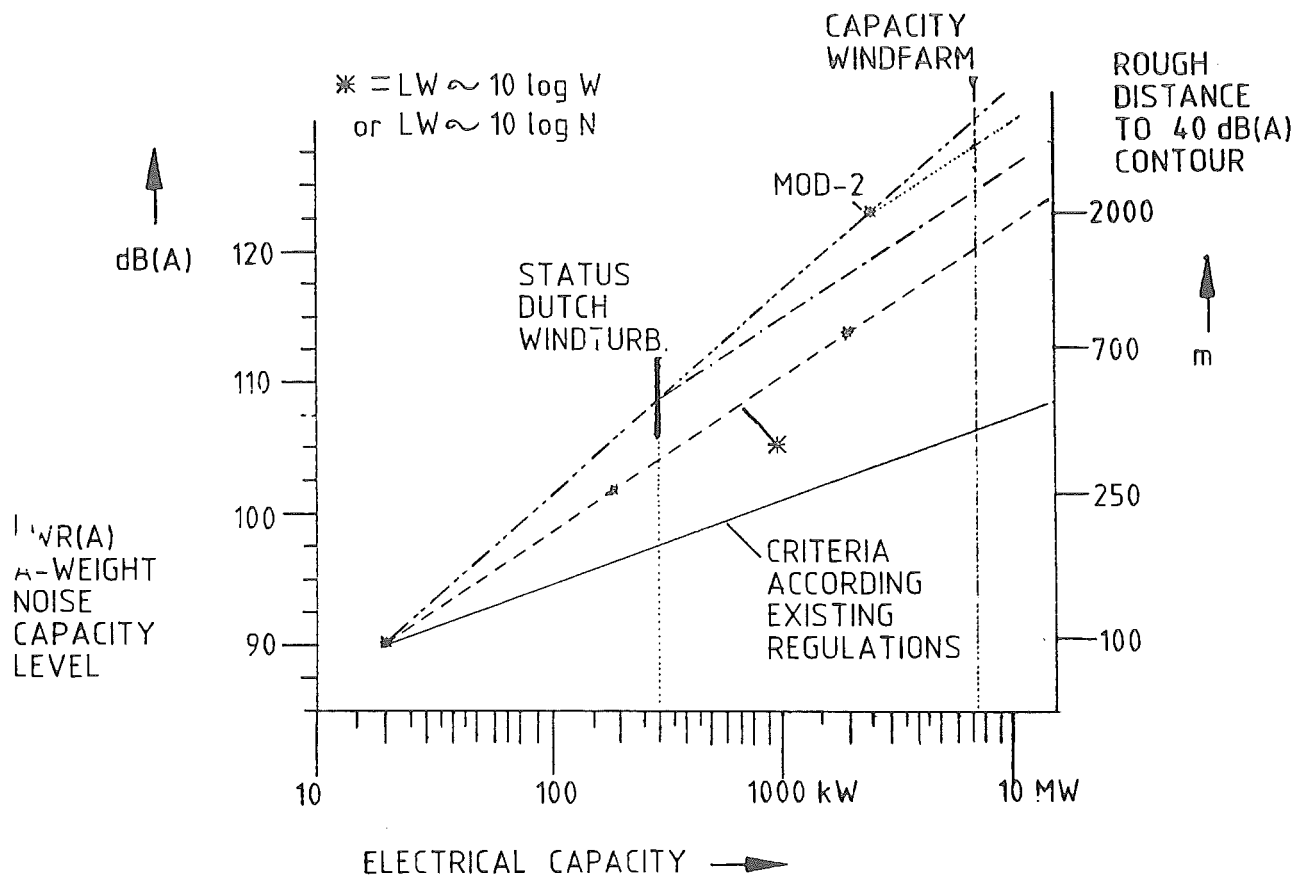
REFERENCE   : 20-kW TURBINE IS NOW ACCEPTABLE
                     (LEVEL 40dB(A) AT ABOUT 100 m

10 × THIS TURBINE : DISTANCE ABOUT 250 m

100 × THIS TURBINE: DISTANCE ABOUT 700 m

MOD-2 (2.5 MW)   : DISTANCE ABOUT 2000 m

WINDFARM WITH MOD-2 TURBINES : DISTANCE ≫ 2000 m

WINDFARM WITH 300-kW TURBINES
OF PRESENT STATUS   : DISTANCE ⟩ 2000 m

FIG. 7

LAY-OUT WINDFARM WITH SAFETY
DISTANCE AND 40 dB CONTOURLINE
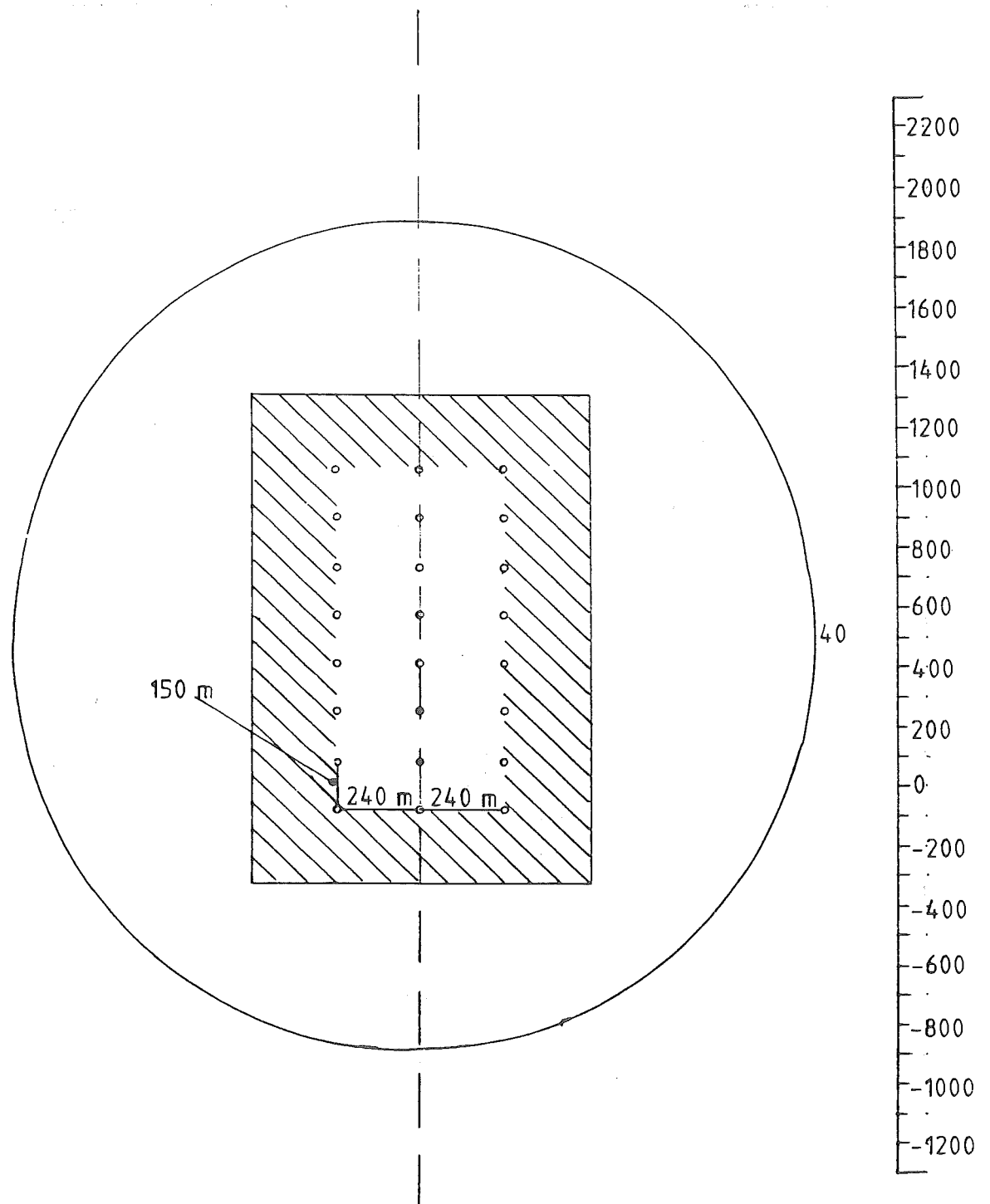
FIG. 8

NOISE SOURCES OF WIND-URBINE COMPONENTS

FIG. 9

FIG. 18

FIG. 19
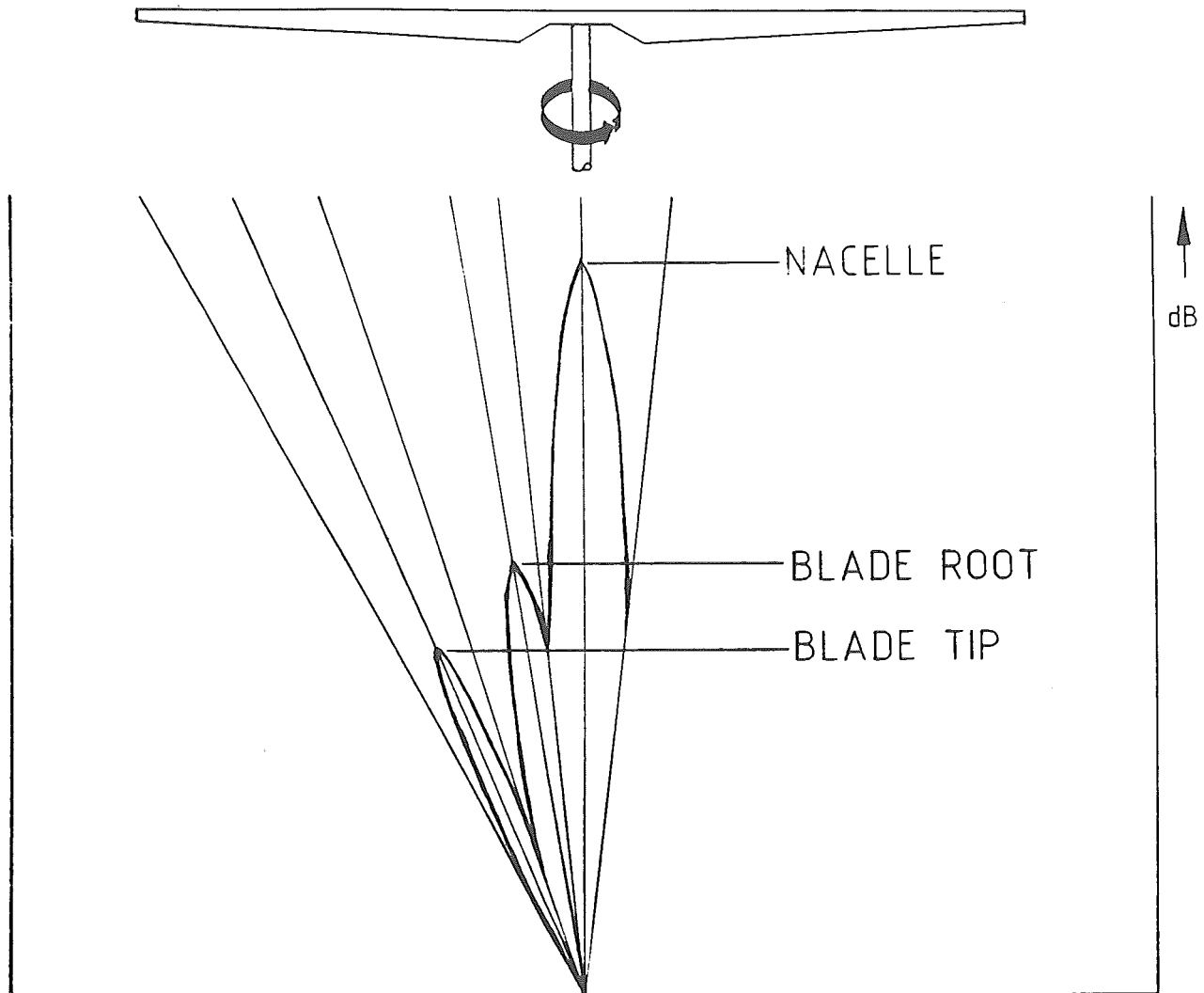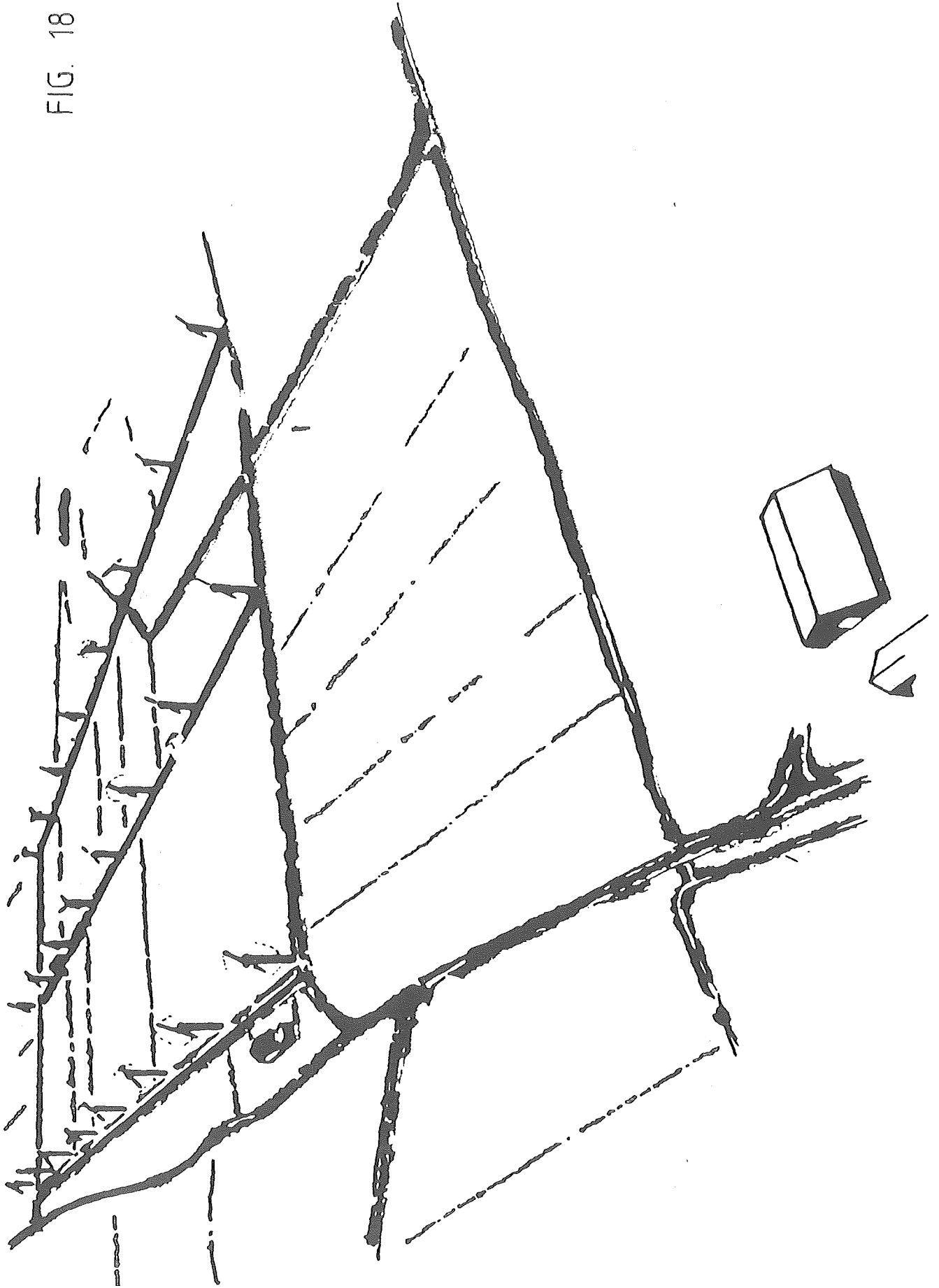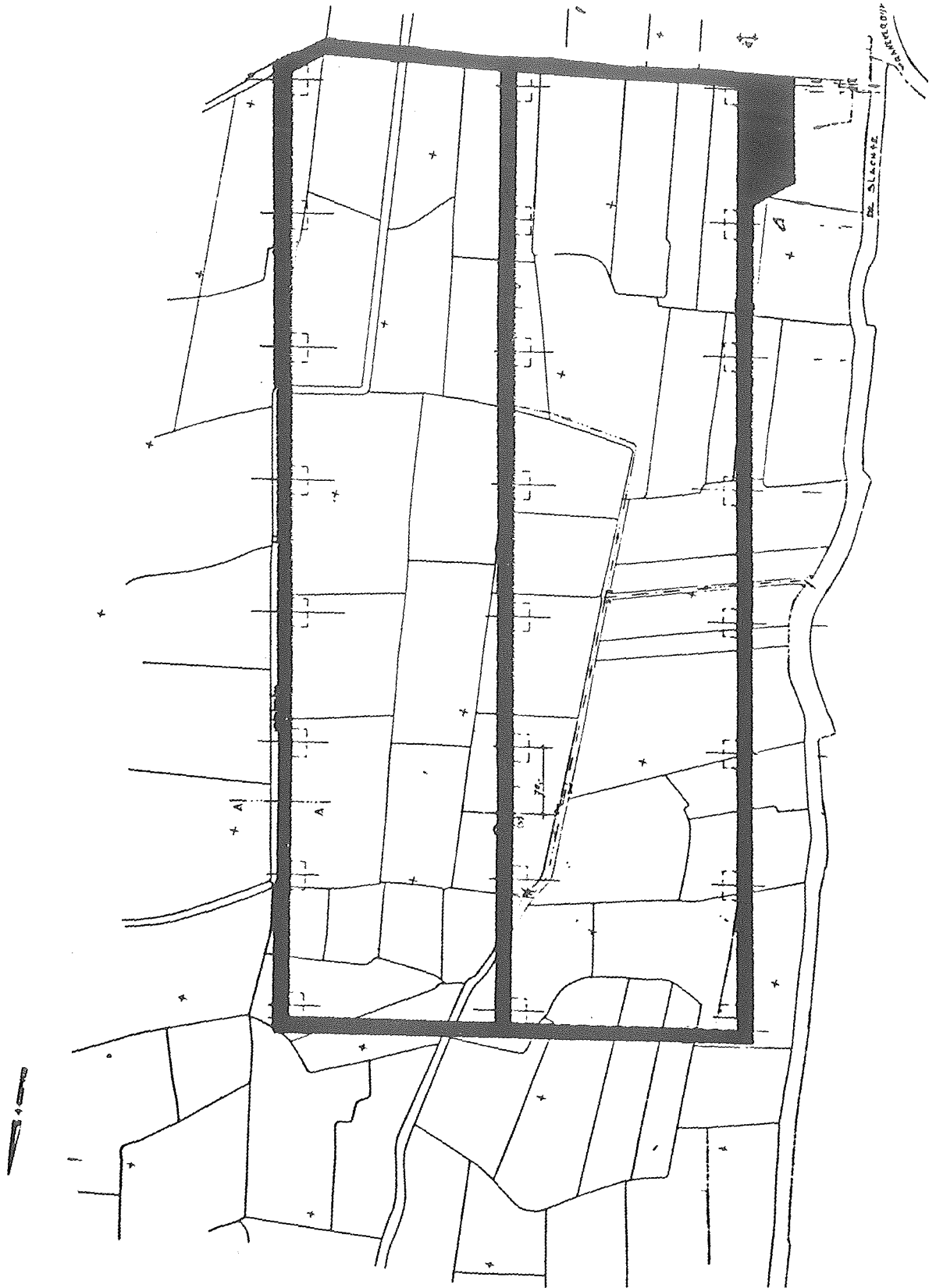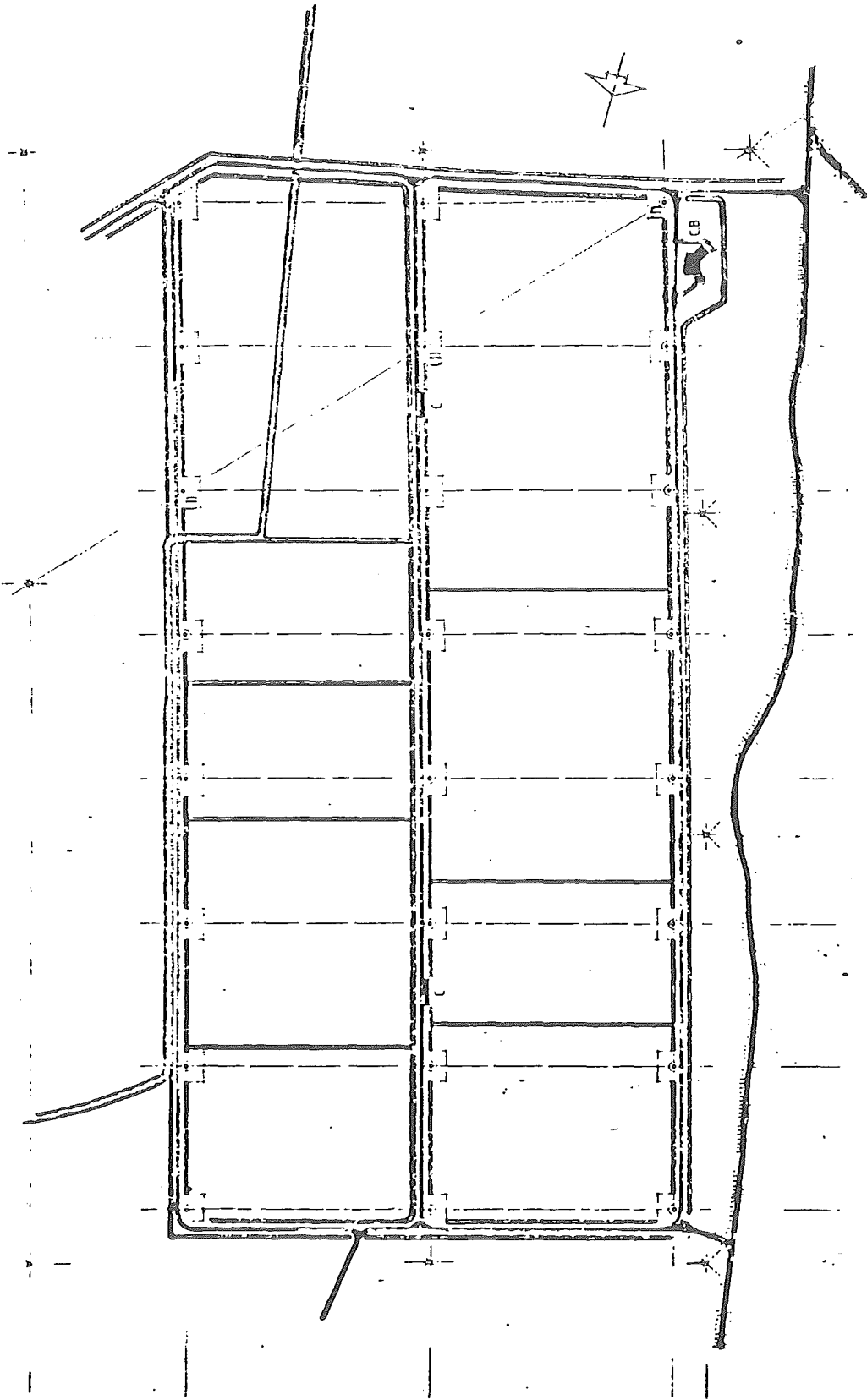
FIG. 20

ORGANISATION DIAGRAM
PROJECT WINDFARM

```
┌─────────────────────┐              ┌─────────────────────┐
│        SEP          │              │  MINISTRY OF        │
│  ┌───────────────┐  │              │  ECONOMIC           │
│  │    OWNER      │  │              │  AFFAIRS.           │
│  └───────────────┘  │              └─────────────────────┘
└─────────────────────┘

                                     ┌─────────────────────┐
                                     │  TECHNICAL          │
                                     │  ADVICE             │
                                     │  COMMITTEE          │
                                     └─────────────────────┘

              ┌─────────────────────┐
              │  SUPERVISION        │
              │  COMMITTEE          │
              └─────────────────────┘

                                     ┌─────────────────────┐
                                     │                     │
                                     │  AMMA               │
                                     │                     │
                                     └─────────────────────┘

┌─────────────────────┐              ┌─────────────────────┐
│  PROJECT TEAM       │              │  NATIONAL           │
│     KEMA            │ ─ ─ ─ ─ ─ ─ ─ │  WINDENERGY         │
│                     │              │  PROGRAMME          │
└─────────────────────┘              └─────────────────────┘
```
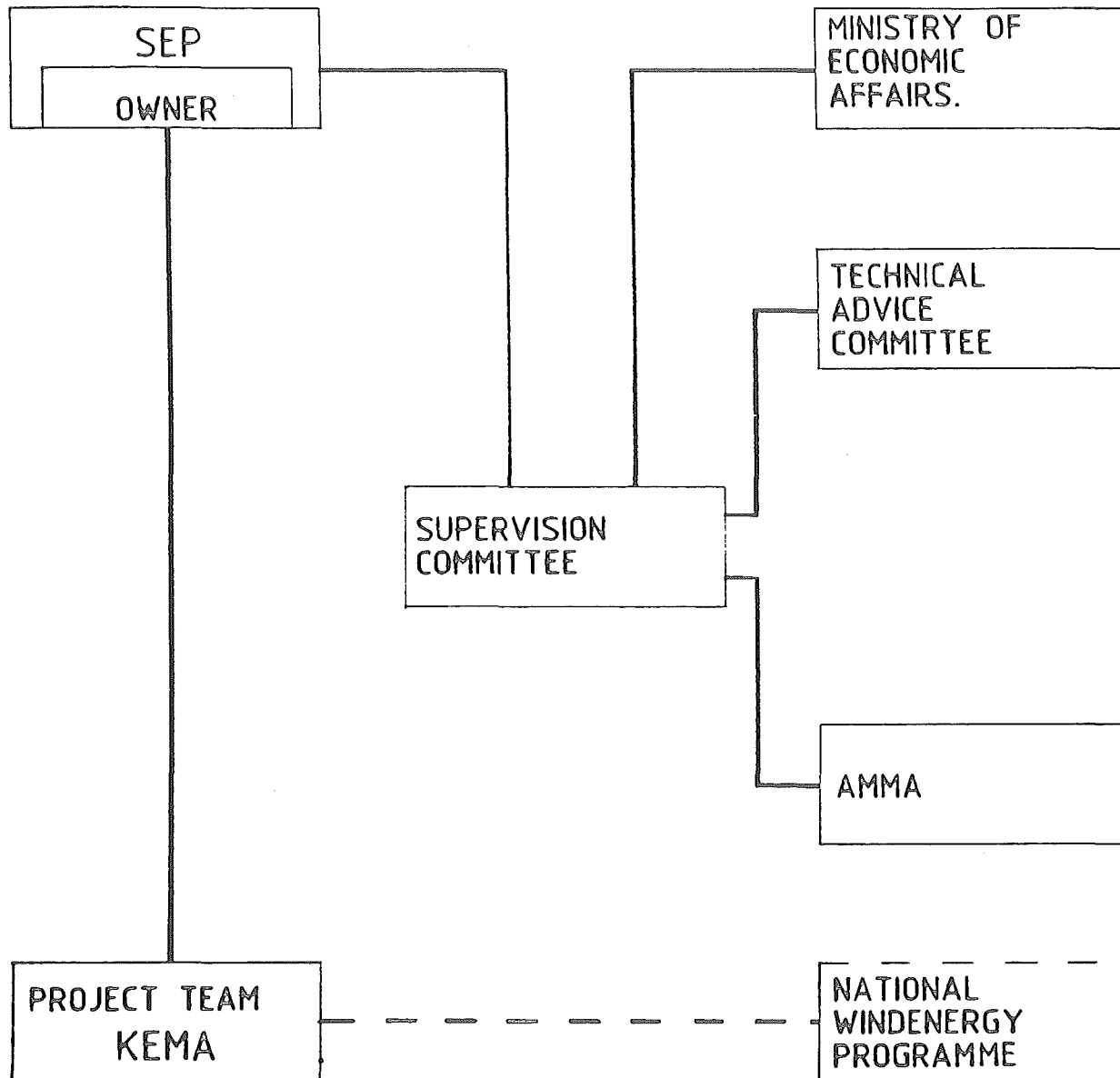
FIG. 21

FIG.6

artists' impression of wind farm.

FIG.10

FIG. 11

184
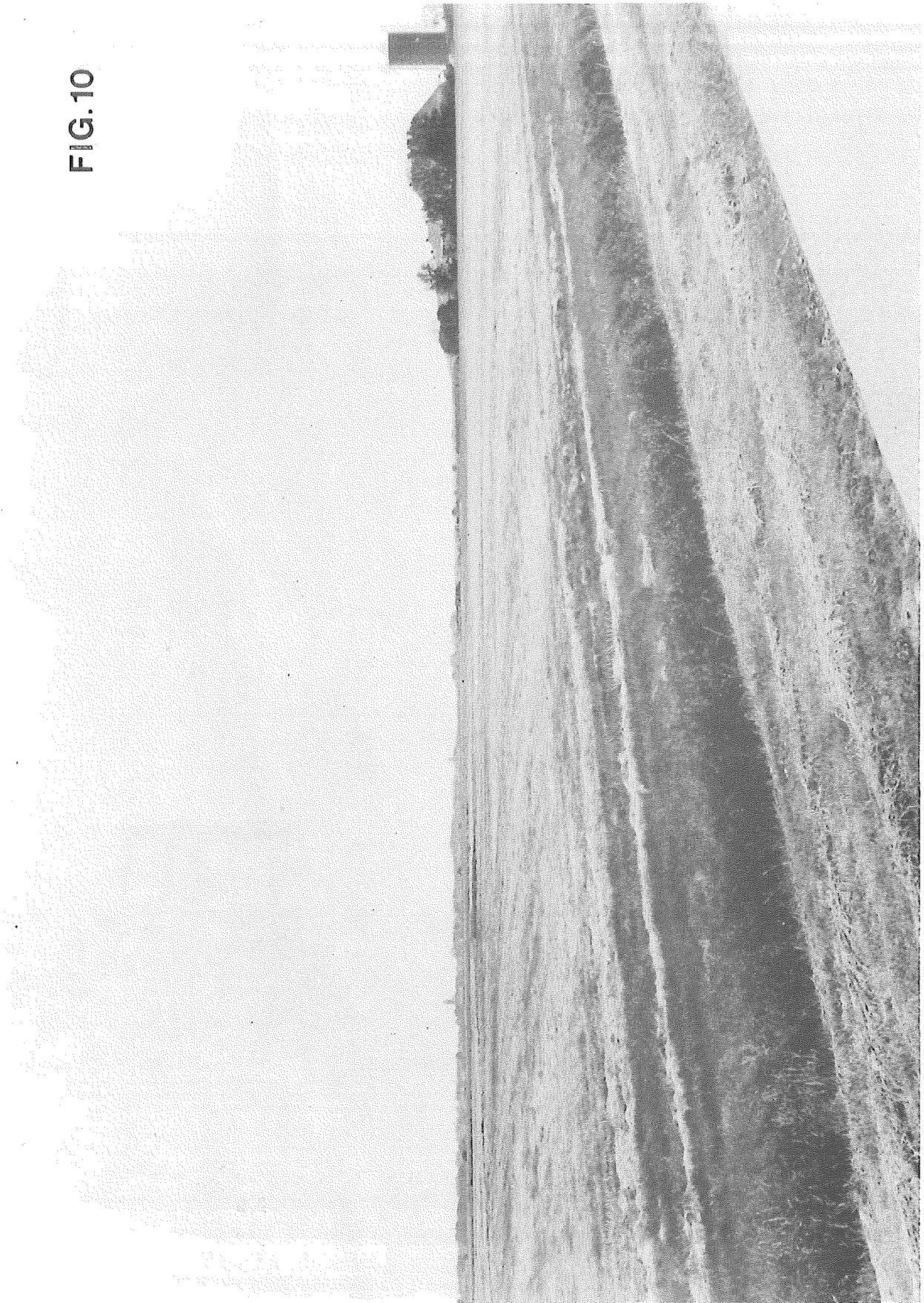
FIG. 12
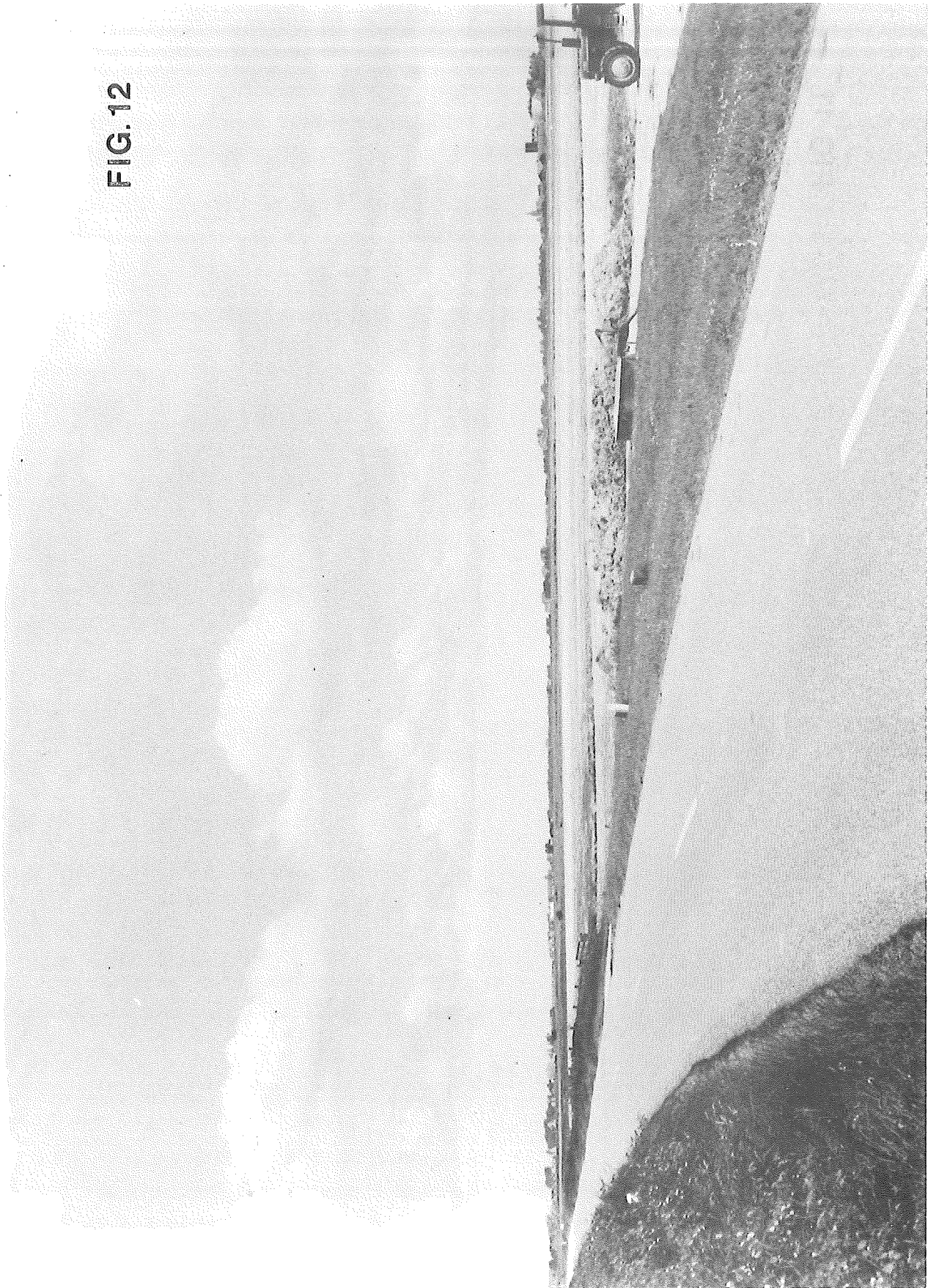
FIG. 13
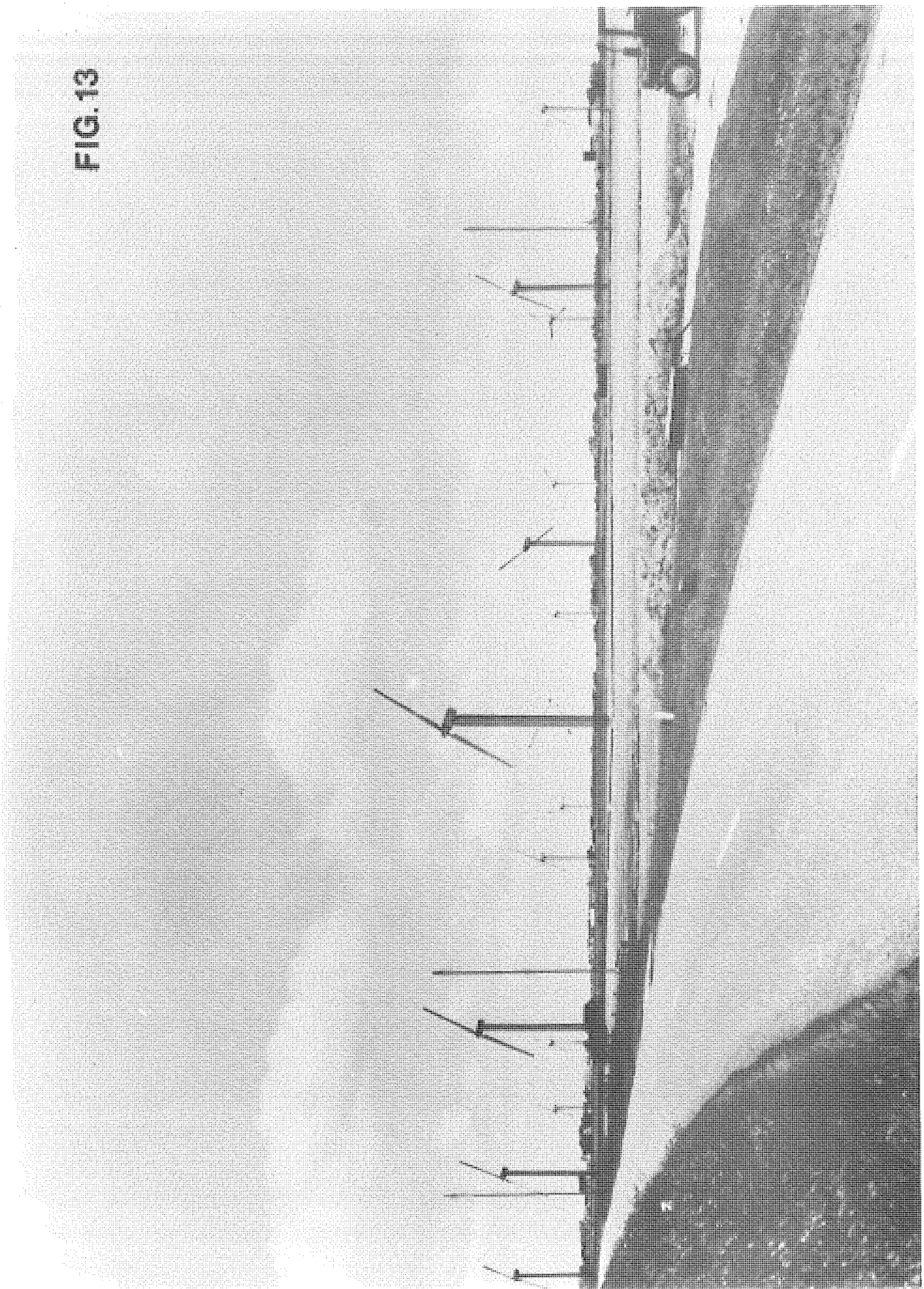
FIG.14
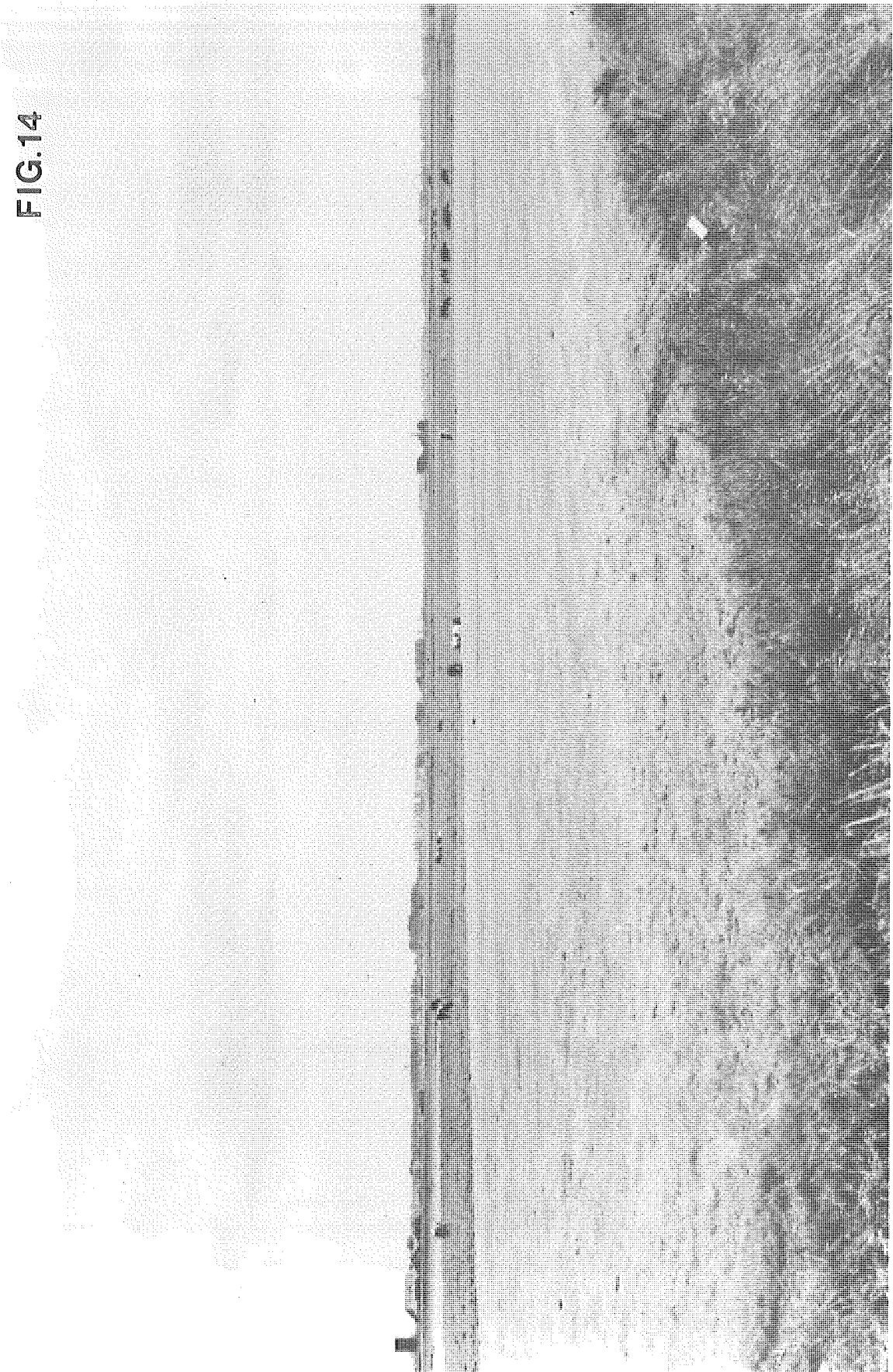
FIG.15
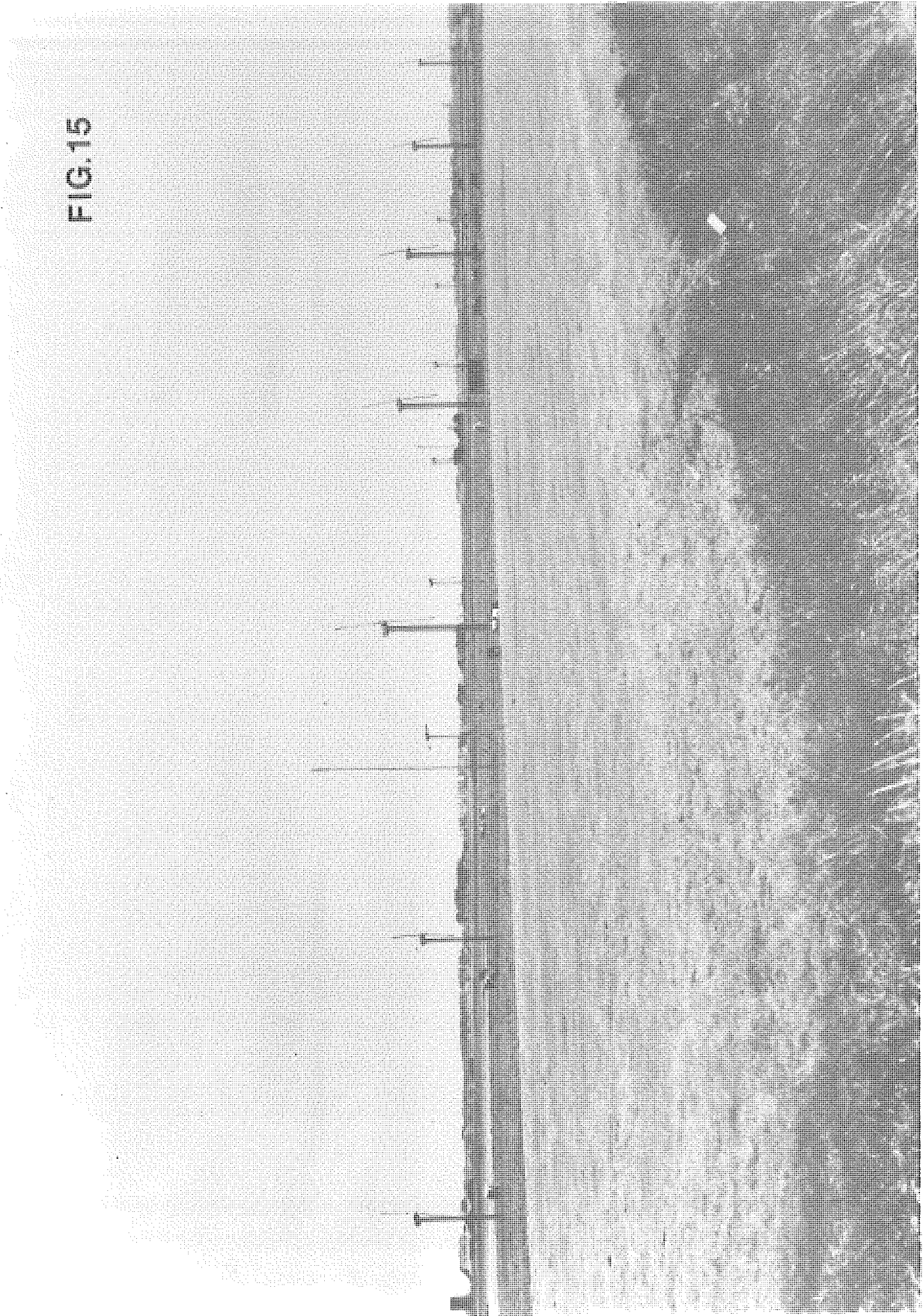
FIG.16
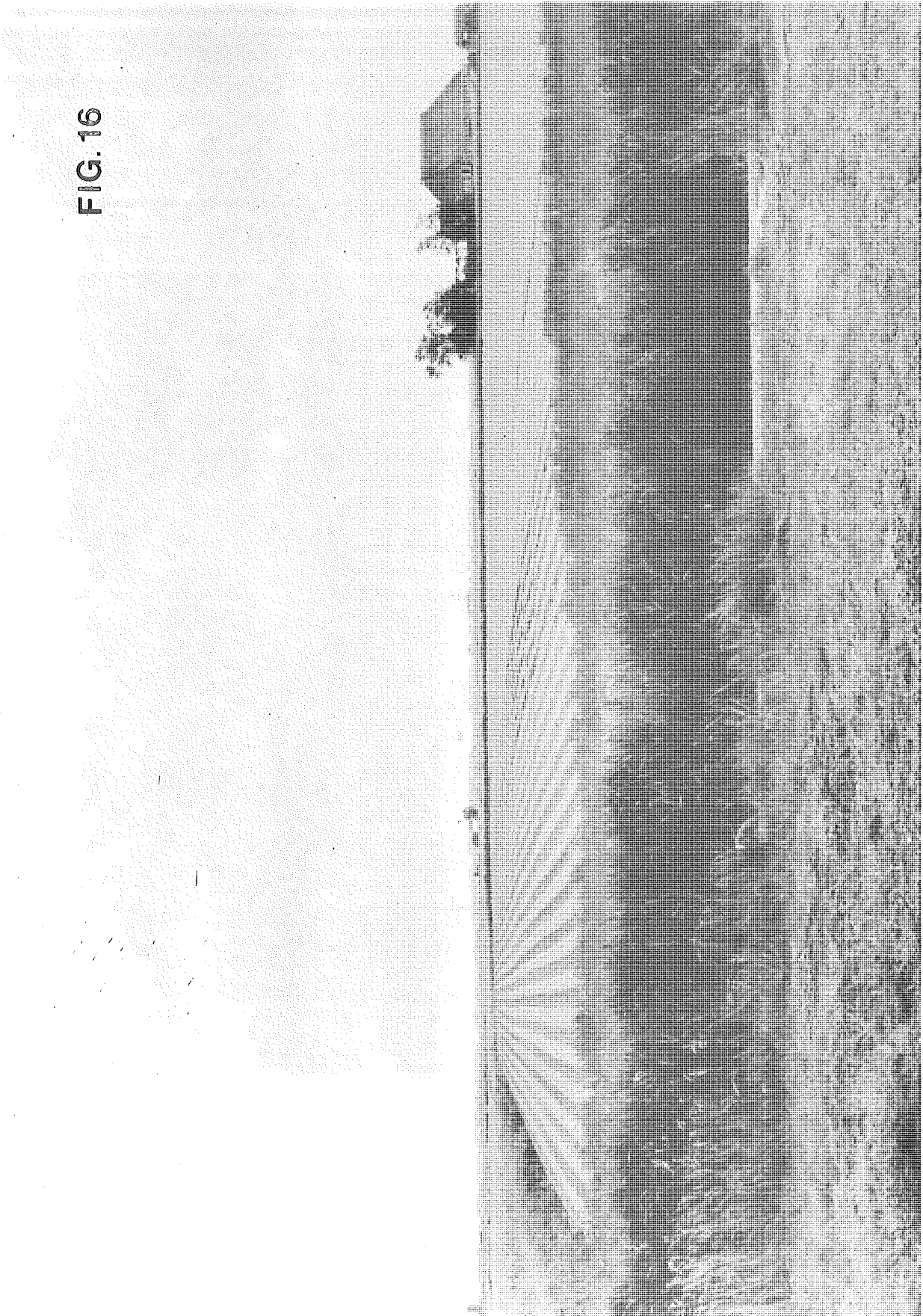
FIG.17
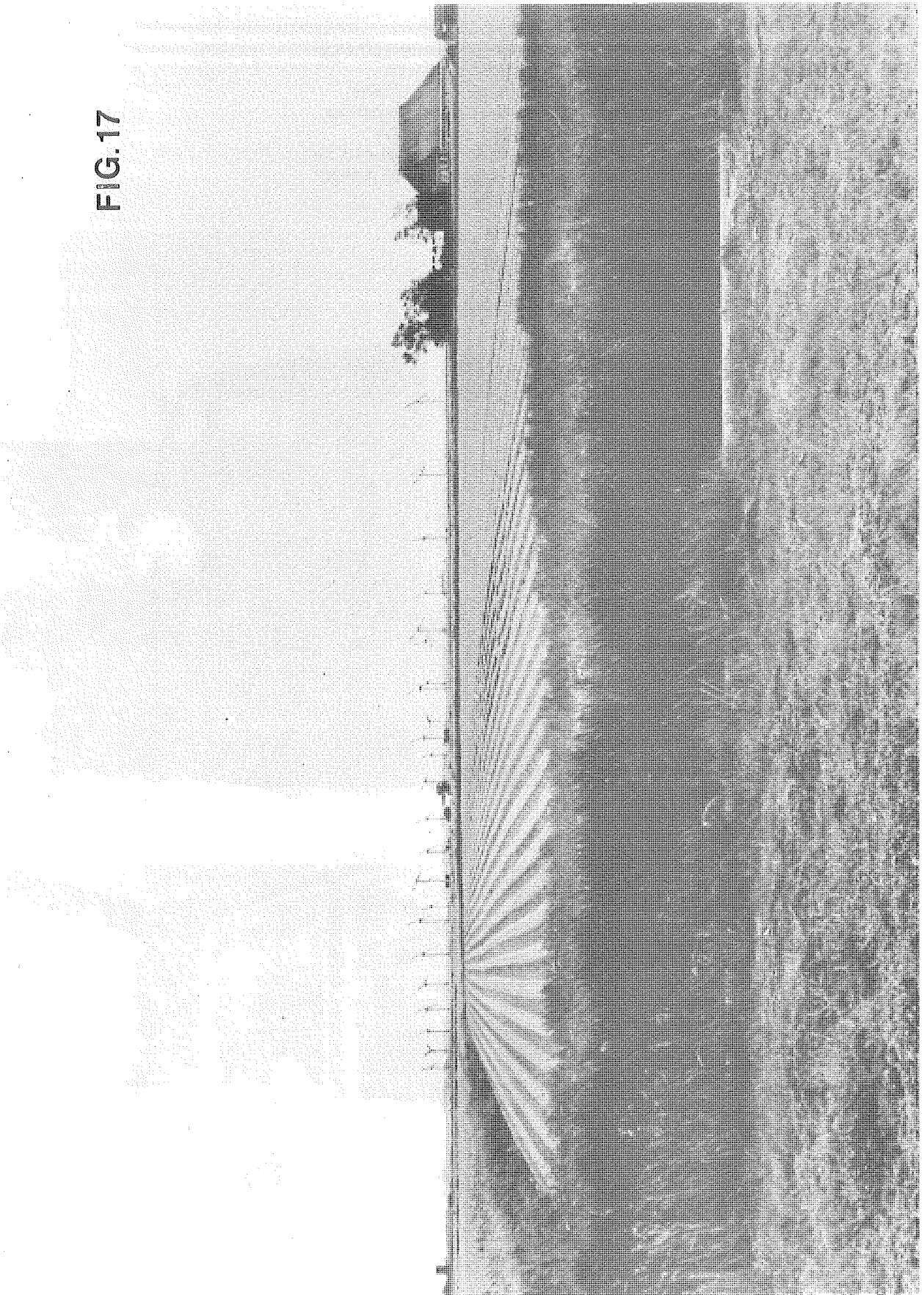
Direct sound measurements with SYNTACAN

What is SYNTACAN?

SYNTACAN is the Synthetic Acoustic Antenna, developed by the Acoustics group of the Technical University Delft, in collaboration with the Institute of Applied Physics TNO-TH. The instrument was developed primarily for measuring industrial noise. **Directivity** is obtained by **synthesis** of the individual microphone signals, giving a resolving power of 1,5°.

SYNTACAN with its experienced crew can be hired. Compared with conventional measuring methods, SYNTACAN is very price competitive. This is caused by on-line data processing and the presentation of the results in polar graphs, which makes nterpretation easy.

Why DIRECTIONAL sound measurements?

In practice, noise sources almost never occur alone. The reason behind the development of SYNTACAN was the need of sound experts for an instrument hat could measure the immission levels of the individual sources on a place that is relevant to the sound immission.

The use of SYNTACAN is recommended under the following conditions:
a. if the position of the noise sources is unknown;
b. if the acoustic powers cannot be calculated from emission measurements;
c. if the sound transmission is too complicated for reliable calculations;
d. if there is too much background noise for normal immission measurements.

In fact there are many cases where SYNTACAN is the only tool to give a reliable determination of the immission levels due to the individual noise sources, at the same time measuring the source directions. Although SYNTACAN has been developed for the measurement of large industrial areas, it can be of great help in all those cases where the lack of directivity of conventional measurement techniques is inadmissible.

For the application of SYNTACAN the same meteorological conditions must be fulfilled as for conventional measurement techniques. Furthermore sufficient space has to be available at the measurement site for installing the antenna (see specifications on page 4). Experience has shown that during a normal working day of 8 hours, measurements can be completed at two sites.
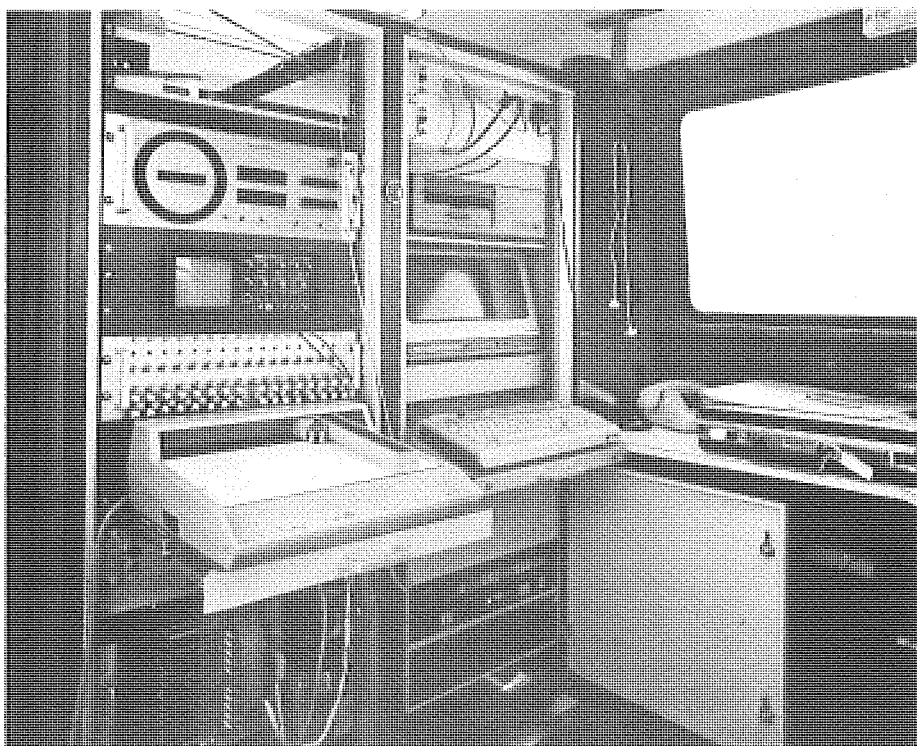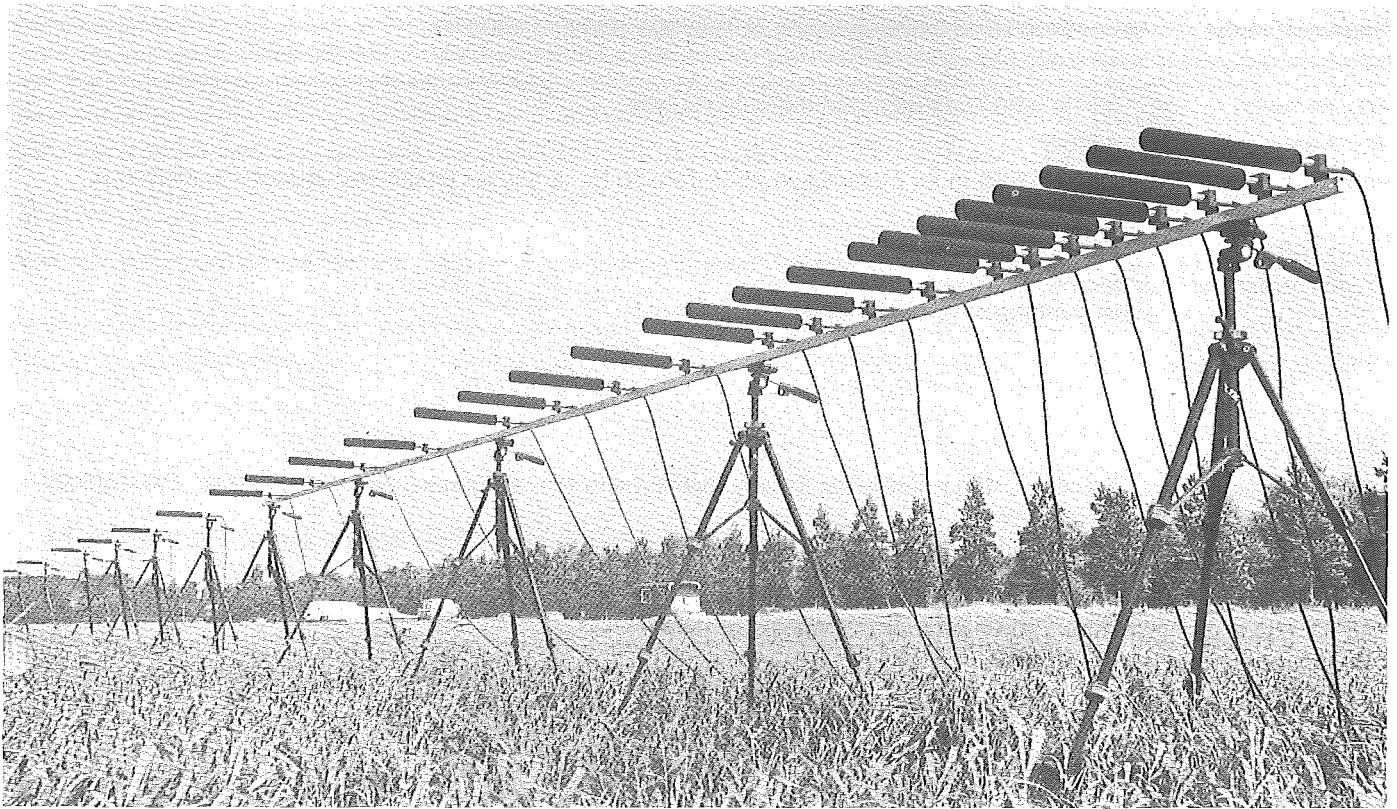
Measurement principle

The Synthetic Acoustic Antenna makes use of a large number of microphones (max. 32), that are placed in a row. Correlation of the microphone signals gives the possibility to analyse the sound field as a function of frequency and of the angle of incidence. This measurement technique necessitates the use of directional microphones, as it cannot distinguish between sounds from front and rear of the antenna. On-line correlation of the microphone signals is done with a powerful data aquisition and minicomputer system that are installed in a motorvan.
The power and flexibility of SYNTACAN is a result of its specially developed software, comprising of:

Calibration and testprocedures
– Absolute calibration of the antenna;
– Microphone check before starting the measurements.

Acquisition
– Choice of the octave bands to be analysed (125, 250, 500 and 1000 Hz);
– Choice of the number of microphones (for measurements with shortened antenna);
– Handtriggering (to avoid disturbance by other sources);
– Averaging over a number of measurements.

Post processing and presentation
– Focussing an any distance;
– Plotting of polar octave diagrams;
– Plotting of the 1/12 octave spectra for any direction between −30° and +30° and integrated over an arbitrary angular range.

The results are obtained at the measurement site, so direct checking of the measurements is possible and, if necessary, the measurement scheme can be adapted.

SPECIFICATIONS OF SYNTACAN

Frequency range	: 90 to 1400 Hz in 4 octave bands of 125, 250, 500 and 1000 Hz.
Frequency resolution	: 1/12 octave band.
Angular range	: $-30°$ to $+30°$ with regard to the antenna axis.
Resolving power	: 1,5 $\pm$0,5°.
Antenna length	: maximal 76,65 m for a resolution of 2° from 90 Hz (a shorter length with reduced resolution is possible).
Focussing	: on any distance.
Graphic presentation	: polar diagrams per octave spectral diagrams for any direction.

LITERATURE

1. M. M. Boone and A. J. Berkhout, "Industrial Noise Source Identification with a Sparsed Microphone Array", Proceedings of Internoise 81, Amsterdam (1981).
2. M. M. Boone, "Opsporing van Industriële Lawaaibronnen met een Synthetische Akoestische Antenne", Publicatie nr. 64 van het Nederlands Akoestisch Genootschap (1982).

FOR FURTHER INFORMATIONS PLEASE CONTACT

Scientific Information:
Department of Applied Physics of TH-Delft
Group of Acoustics
Lorentzweg 1, Delft
Postbox 5046, 2600 GA Delft
Telephone 015-781471
ir. M. M. Boone

Business information:
Institute of Applied Physics TNO-TH
Stieltjesweg 1, Delft
Postbox 155, 2600 AD Delft
Telephone 015-569300 (after 1 February 1983: 015-788020)
Telex 38091 tpddt nl
ir. W. Kooijmans

H. Zwahr

Visual Impact of GROWIAN and Resulting Recommendations for
Siting of Large Wind-Energy-Converters

Pictures of wind energy converters usually are taken from
a close distance. Thus they look very impressive and grand.
At least in the eyes of people who are occupied in wind
energy.
A lot of people may disagree though, as can be derived from
remarks like

> " forest of wind mills", or
>
> " optical pollution by wind mills".

To find part of an answer to the questions put forward in
the invitation to the 11th IEA-expert meeting, those questions
were formulated anew, giving them sort of a different sense:

- From about what distance does a large wind-energy-
  converter like GROWIAN become dominant in it's
  surrounding?

- What can be done to lessen the impact on the landscape?

- If there should arise a need for a larger amount of wind
  turbines, how closely can they be placed together without
  having too much of an impact on the surrounding area?

The approach to answer these questions was a very personal and
probably not a very scientific one:

- A series of pictures of GROWIAN was taken from different
  distances, ranging from 15 to 1,5 km. The points, from
  which the pictures were taken, are indicated with numbers
  on fig. 1.

- The pictures were taken without any photographic ambition
  for beauty, i.e. using a foreground or some sort of
  optical frame, rendering more depth to a picture. As a
  matter of fact, open spaces were selected to stress the
  visual impact of the machine.

- A 50 mm lens was used, which renders a somewhat wide-angle
  effect; so the pictures seem to be taken from a point a
  little further away from the object than the actual distance.
  This error appears to be negligible .though.

- The pictures were taken on a very clear day with a visi-
  bility of more than 20 km, which is very good for the
  northern part of Germany.

The pictures, taken from points 1 to 8, are shown in fig. 2 to 9.
Point 1 has an elevation of about 40 m above ground (bridge across
canal), points 6 and 8 from an elevation of about 5 m above the
surrounding terrain (standing on an old dike).

Conclusions:

- The GROWIAN-wind-energy-converter gets dominant from a
  distance of less than three kilometres.

- Light colours should be used to make it less visible.
  This is illustrated by fig. 10 and 11, which where taken
  from view-points 10 and 11. The shadow-side makes the
  structure appear dark, thus rendering it more outstanding
  against the light sky.

- To avoid an accumulating effect, the turbines should not
  be placed together too closely. then the "forest-effect" won't
  even creep up in people's mind. This can be illustrated by fig. 12,
  which was taken just south of the city of Brunsbüttel. Masts about
  50 m high (standing appr. 400 m apart) "disappear" at a distance of
  about 2 km, because not only perspective makes them look smaller but
  also because the flaire in the air dissolves the contours.

An additional effect should also be taken into account which cannot
be accounted for by "static" pictures.

The human eye will detect moving objects much easier than things
standing still. Thus the rotating blades of a wind turbine in
operation will be noticed much earlier than one standing still.
And only the later effect can be simulated by photo-mountings.

Another "dynamic" effect, which was observed at the GROWIAN-site,
may cause some problems, if houses are located near a windmill.
During late autumn, winter, and early spring the sun doesn't rise
very high above the horizon, causing long shadows. When these shadows
of rotating blades reach the living quarters, they change the inten-
sity of the light in the effected rooms with the frequency of the
rotor-blades, causing something like a strobe-effect. Staying in
these rooms or   doing work which affords a certain degree of
concentration becomes practicly impossible according to some people
living near GROWIAN. Siting of a wind turbine should take this
into account.

Fig. 1: Area map, markers indicate
points from where pictures
were taken
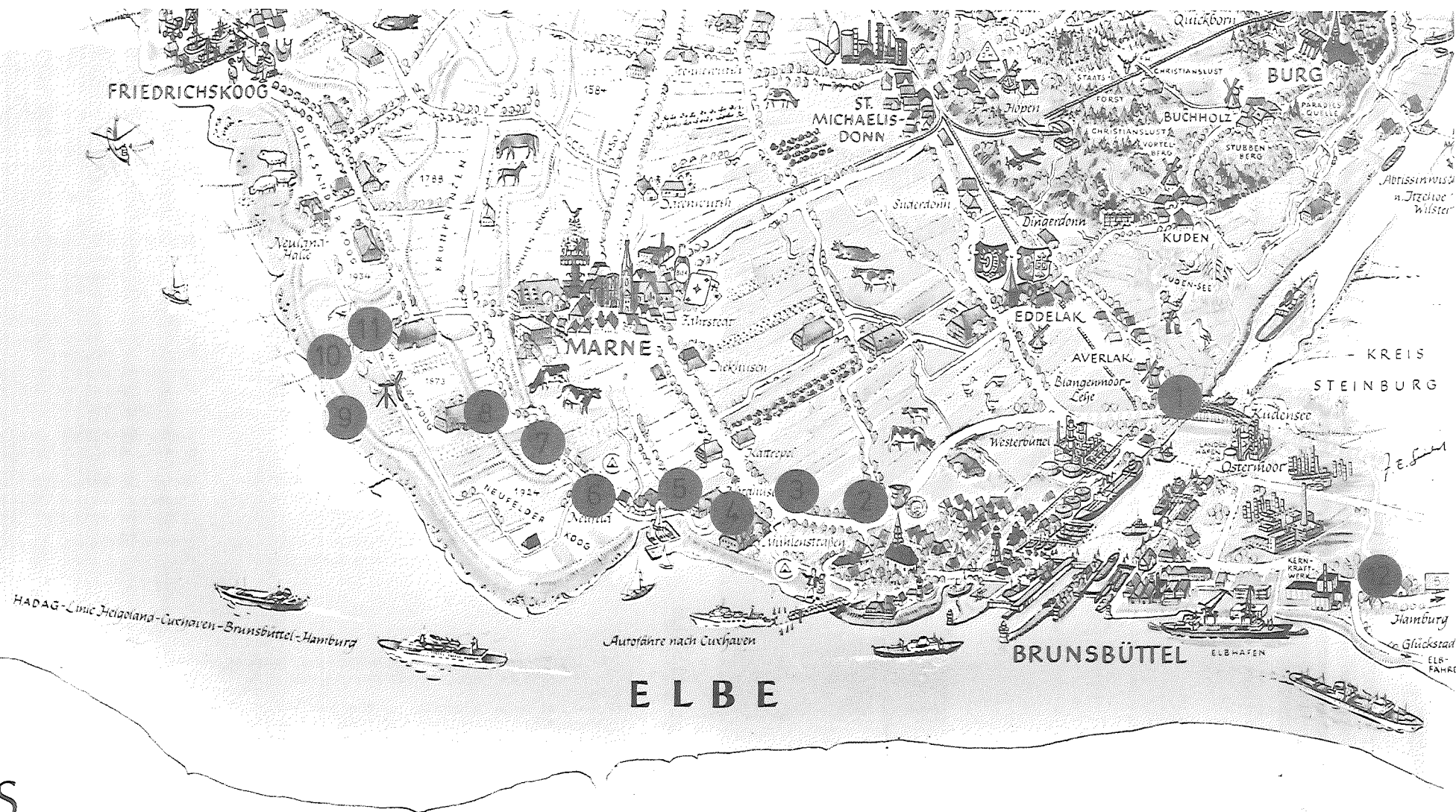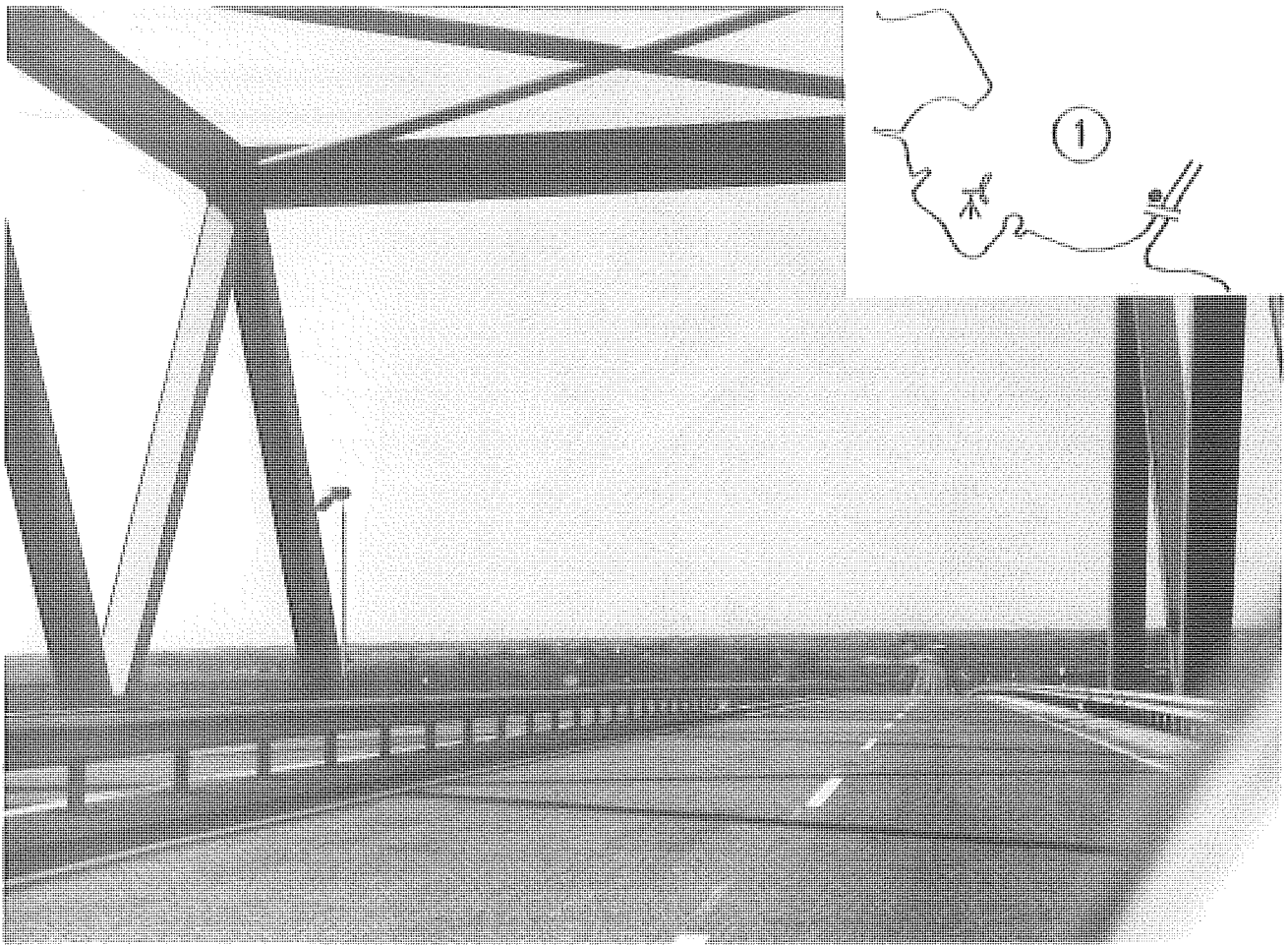
Fig. 2: distance appr. 15 km

Fig. 3: distance appr. 9 km
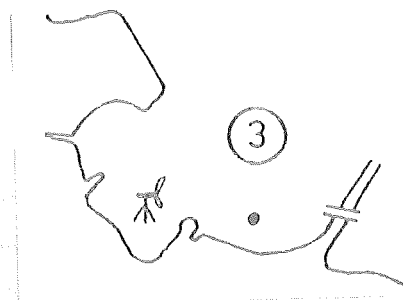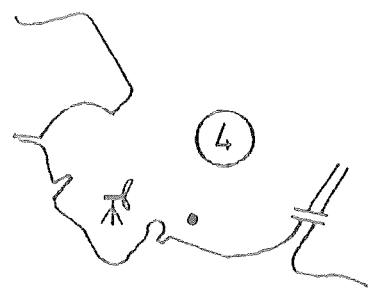
Fig. 4: distance appr. 7.5 km
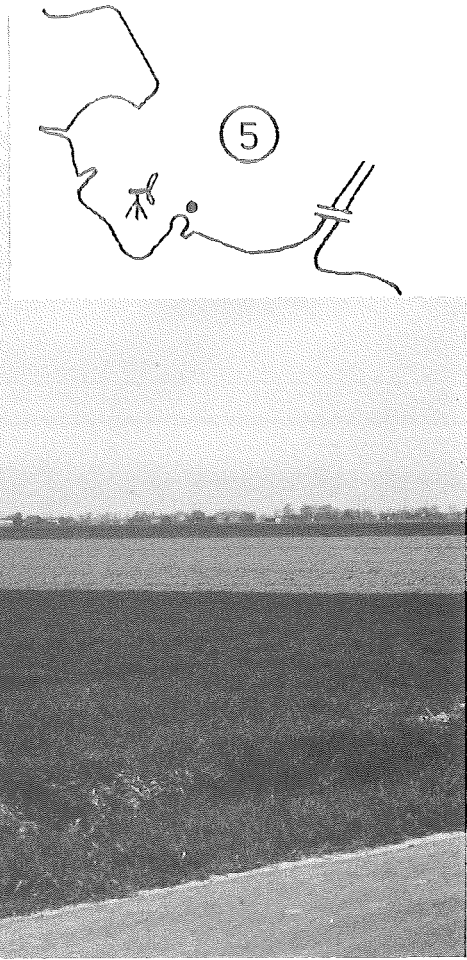

Fig. 5: distance appr. 6.5 km

Fig. 6: distance appr. 5.5 km

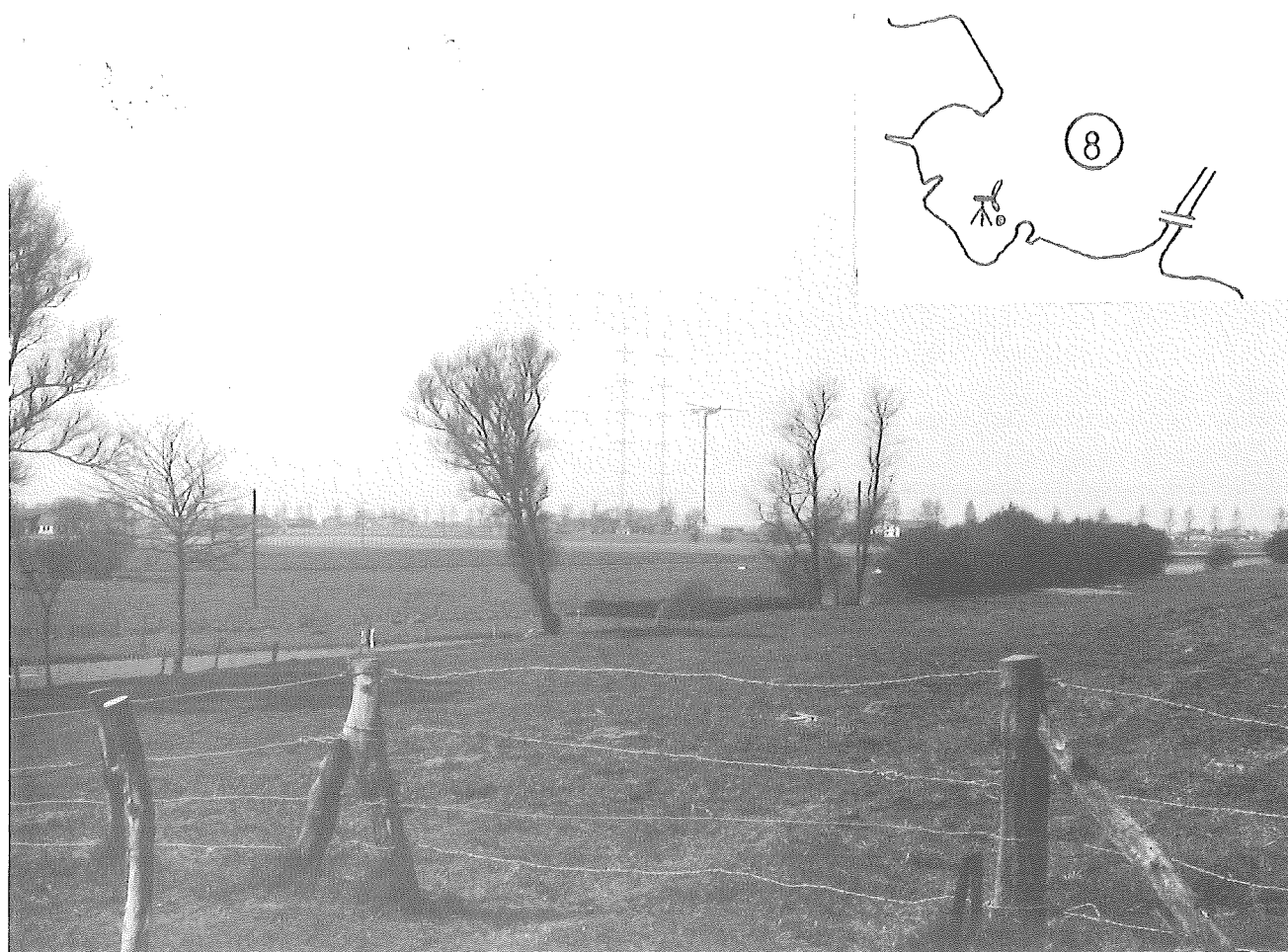Fig. 7: distance appr. 4 km

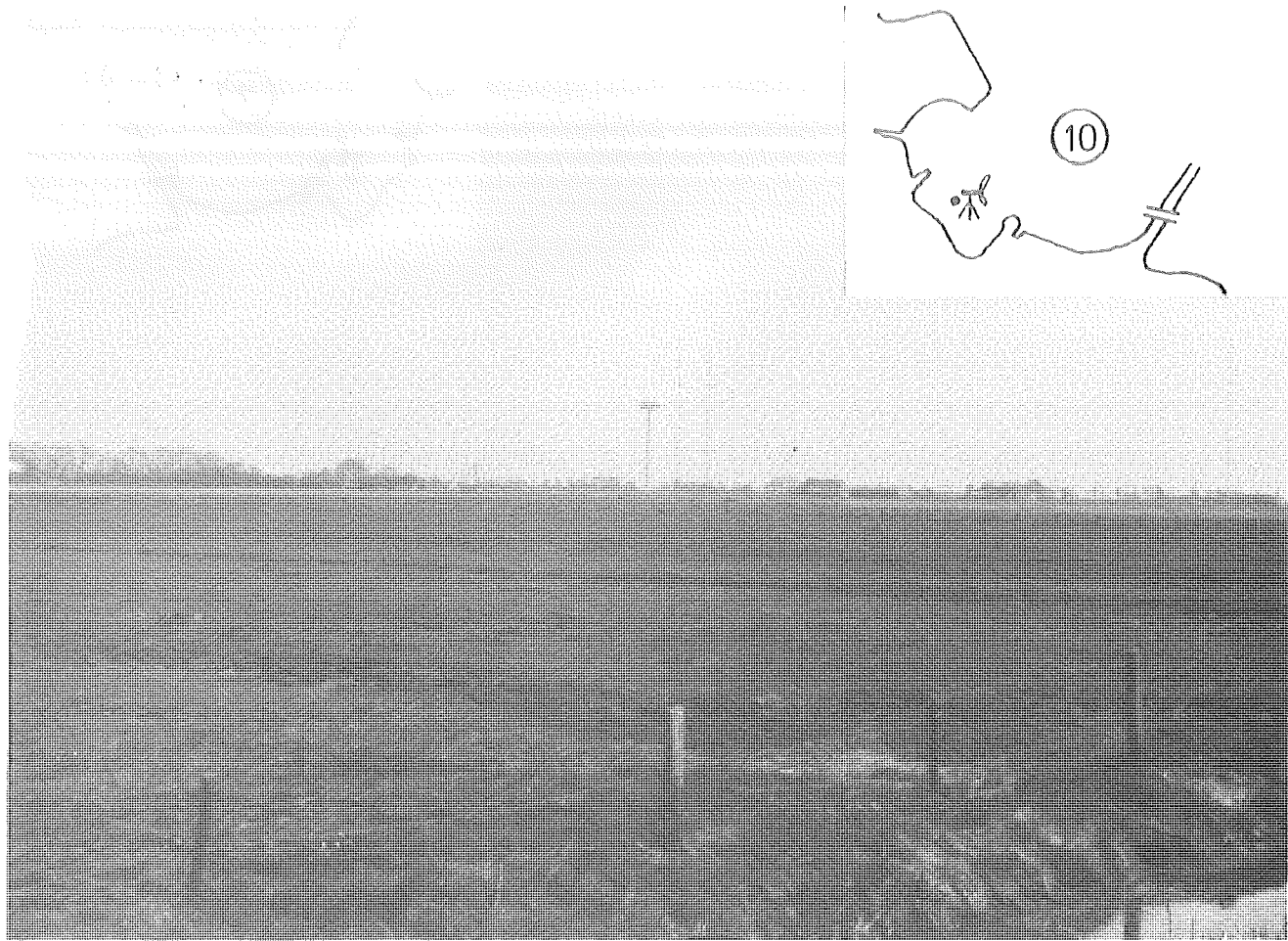Fig. 8: distance appr. 3 km

Fig. 9: distance appr. 1.8 km

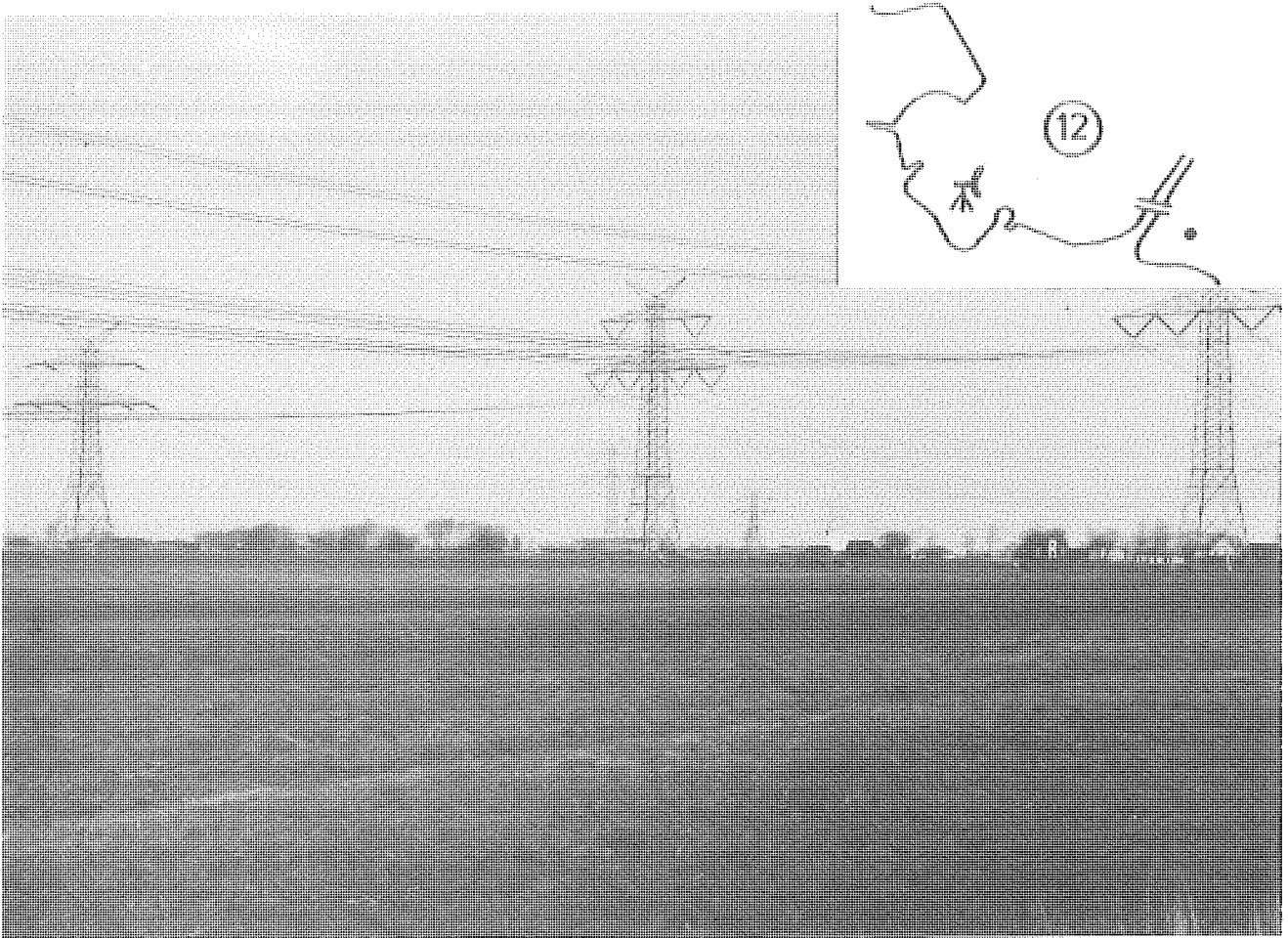Fig. 10: distance appr.0.8 km

Fig. 11: distance appr. 1 km

Fig. 12: power lines near Bruns-
buettel

Visit to test facility Stötten, Mai 9, 1984, including the
Voith WEC 520 turbine

The annual energy production of various wind energy plants
in selected locations

Hans-Ulrich Banzhaf
Wolfgang Weber

C o n t e n t s

Synopsis

Described are the design possibilities for wind energy plants which differ from each other in terms of specific power. The annual energy output figures of two different wind turbine designs with an installed power of 316 kW each, in two different locations, one in the interior and one in a coastal region, are compared with each other. In doing so, one sees that with the larger plant which is designed to a lower specific power gives a 2-3.5 times greater energy yield than the design with the higher specific power. Because, however, the larger plant also demands a higher price, one should pay attention when comparing the two plants not only to the installed power, but also to the great difference in annual energy production.

1. Introduction

Already in pre-industrial times, windmills were erected in specially selected locations, places predestined by their topography. Many open coastal regions, hill crests, and highland plains still give evidence today of their suitability for the operation of wind turbines. Their special suitability still exists today, although a diversified picture is yielded when, on the one hand, the systematic knowledge of metorology and on the other, the aerodynamic design of modern wind energy plants are applied for an optimization of possible energy production from wind.

2. Wind data

For a given location, the wind conditions are determined from a large number of wind data, most of them recorded as the three major factors related to one year:

- the percentage wind direction distribution, also known as compass card,

- the mean annual wind velocity $\bar{c}$

- the cumulative frequency distribution of wind velocities.

The second two of these factors are particularly important for the exploitation of wind energy. While the magnitude of the mean annual wind velocity serves rather as an orientation on high or low general wind conditions, the cumulative frequency distribution can be utilised for the calculation of energy yield to be anticipated.

One difficulty in this is the fact that the frequencies of wind velocities are often formed from hourly mean values and therefore - because of the arithmetical determination - important information on exploitable energy of the wind, which is related to the 3rd power of wind velocity, is lost. Better data for an energy analysis are therefore obtained from measurements which are processed, for example, from the normal meteorological 10-minute mean values.

The simply calculated annual hourly figures for the respective wind velocity occurring, however, are exploited differently by the wind turbines. Probably the best efficiency is attained by plants which can be regulated by rotor blade adjustment. These are mainly to be found on medium and large-sized wind energy converters. It is to this group that Voith wind turbines also belong.

3. Design possibilities for wind energy plants

3.1 General principles

The available wind power P_W is calculated from the wind velocity c, the disc area A of the rotor and from the density of air ϱ in the relationship

$$P_W = \frac{\varrho}{2} \cdot c^3 \cdot A \qquad (1)$$

with

$$A = \frac{\pi}{4} \cdot D^2 \qquad (2)$$

Whereby D is the rotor diameter.

The available wind power, however, can only be partly utilised by a wind energy plant due to losses occurring at the rotor blade. This is expressed by the power coefficient

$$c_p = \frac{P_R}{P_W} \qquad (3)$$

in which P_R is the power absorbed by the rotor of the turbine.
According to optimum calculations as undertaken by Betz /1/, the power
coefficient cannot exceed

$$c_{pid} = 0.59$$

The actually attainable power coefficient $c_p < c_{pid}$, with the selection of
a specific design, is dependant upon the design wind speed c_A.

In consideration of the plant as a whole, this power coefficient is reduced
still further by mechanical and electrical losses. These losses, however,
will be overlooked in our further consideration, since the relation of results
is not impaired by them.

3.2 The characteristics of a wind turbine

The characteristic of a wind turbine is used for an evaluation of its design and
operating behaviour as shown in figure 1, as an example, for the Voith WEC 520.
Here, the power coefficients c_p have been plotted in relation to the tip speed
ratio

$$\lambda = \frac{u}{c} \tag{4}$$

whereby

$$u = \omega \frac{D}{2} \tag{5}$$

is the tip speed of the rotor blade. Selected as parameters for wind turbines with
adjustable rotor blades are the rotor blades angles $\Delta \beta s$. Plotted as second abscissa
in the opposite direction is the wind velocity c at rotor full speed.

The plant can be started when the wind velocity at point (1) is high enough for
the idle-running losses of the plant to be covered. From the starting wind velocity
up to attainment of full power at point (3) the plant is operated on the envelope
of its characteristic range. When the wind velocity c increases, i.e. with a
further decreasing tip speed ratio λ the rotor blade is pitch-controlled in such
a way that the full power is not exceeded. For this reason, between point (3) and
the high wind cut out velocity (4) the plant no longer operates on the envelope of
its characteristic range, but on the power limit, and thus on a line of constant
power.

The highest power coefficient c_p is attained at wind velocity c_A for which the wind turbine is designed (point (2)). For the wind velocities deviating from the design point, the power coefficient decreases, also with adjustable rotor blades. The decrease for a wind turbine with constant rotor blade angle, however, is greater as can be seen in fig. 1, e.g. from the course of the dashed curve $\Delta \beta s = + 1^{\circ}$.

3.3 Technical data of the Voith WEC 520

The WEC 520 has a rotor diameter of $D = 52$ m. At its design speed $n = 37$ 1/min, a tip speed of $u = 100.7$ m/sec ist attained at the tips of the rotor blades.

It can be started at a wind velocity $c_s \sim 4$ m/s (point (1)) and reaches the highest power coefficient at a design wind velocity of $c_A = 6.3$ m/s (point (2)). As early as the wind velocity $c_N = 8.7$ m/s, the WEC 520 delivers its full power of $P_{RN} = 316$ kW (point (3)). The cut out velocity is $c_{zul} = 25$ m/s (point (4)).

3.4 The specific power rating of a wind energy plant

Often, the specific installed power

$$\pi = \frac{P_R}{A} = \frac{4P_R}{D^2} = c_p \cdot \frac{\varrho}{2} c^3 \tag{6}$$

is used as a characteristic value for a plant. This can easily be calculated from the technical data of a wind turbine, namely, the installed generator power P_R and the rotor blade diameter D. Low specific, installed powers of $\pi = 100 - 150$ W/m² point to designs for territories with low wind velocity, and high values of $\pi = 400 - 500$ W/m² to designs for territories with high wind velocity, such as coastal regions.

If one observes not only the range of the characteristic curve along which the rated power is obtained, then a curve of the specific power π as per equation (6), versus wind velocity is yielded as plotted in fig. 2, e.g. as curve a' for the WEC 520. At the same time, fig. 2 shows again the control characteristic of the wind energy plant, e.g. as curve a for the WEC 520. This corresponds to the envelope of the characteristic range from fig. 1 between the starting point (1) and point (3) at which the rated power is reached, or the power limit line between point (3) and the cut out point (4). The points have been plotted with the same designations in the control characteristic a and in the curve of specific power a' with '.

From the course taken by curve a' it can be seen that, above the point (3'), the specific power is constant and corresponds to the commonly used specific installed power.

Below this point, however, and therefore in the range of the design point (2'), it is dependent upon wind velocity, and can thus no longer be so simply calculated from the installed generator power.

From the control characteristic of the plant (curve a) it can be seen that the rated power point (3) is no distinct point on the curve, but that it is determined by the combination of a specific generator with a wind turbine rotor. Only by a variation of generator size within a wind energy plant can it be shifted as required along the control characteristic curve. Normally, however, the design is so selected that the point (3) is placed slightly to the right of the optimum in the direction of higher wind velocity. For this reason, the specific installed power corresponding to point (3') can only be used for a rough assessment of a plant.

The more important characteristic value which describes the aerodynamic design of the plant is the specific power

$$\overline{\pi}_A = \frac{P_{RA}}{A} = c_p \cdot \frac{\mathcal{S}}{2} \circ c_A^3 \qquad (7)$$

at the optimum point (point (2)).

One thus obtains, e.g. for the WEC 520, on the power limit at point (3') at a wind velocity of $c = 8.7$ m/s, a specific installed power of

$$\overline{\pi}_N = 149 \ W/m^2$$

while, at the optimum point (2') at a design wind velocity $c_A = 6.3$ m/s a specific power of

$$\overline{\pi}_A = 69 \ W/m^2$$

is yielded. It can be seen that both values deviate greatly from one another, although they are to be used as a means of assessment of the same plant.

3.5 Alternative designs

By the selection of alternative design wind velocities c_A for the optimum point, the whole control characteristic versus wind velocity can be shifted. In fig. 2, the WEC 520 design is compared with an alternative design (curve b) which corresponds approximately with the characteristic of the MAN Growian turbine. The design wind velocity c_A was chosen here as 10 m/s. This, according to Gl. (7), with an optimum power coefficient c_p = 0.45, would yield a specific power of

$$\overline{\pi}_A = 281 \text{ W/m}^2$$

If this control curve were applied to a wind energy plant with a rotor blade diameter of 52 m, it would be possible (e.g. in point (3) of curve b) to install a generator with

$$P_{RN} = 850 \text{ kW}$$

With this, the specific installed power of

$$\overline{\pi}_N = 400 \text{ W/m}^2$$

would be attained at a wind velocity of

$$c_N = 11.8 \text{ m/s}$$

The course of specific powers versus wind velocity is again shown as curve b' in fig. 2.

The alternative design exploits the range of high wind velocity by a better power coefficient. At the same time, however, the lower wind velocities with a lower power coefficient give a low energy production. Additionally, with this design, the start-up of the plant will only occur with higher wind velocities.

Through the selection of a higher specific installed power, the power of the WEC 520 is already reached with considerably smaller rotor blade diameters. A decrease in length of the rotor blade and then, possibly, a decrease in mast height can then lead to considerable reductions in costs for the plant as a whole. In the case of a design with a specific installed power of

$$\overline{\pi}_N = 400 \text{ W/m}^2$$

a rotor blade diameter of only

$$D = 31.7 \text{ m}$$

is calculated for the power of the WEC 520 (with D = 52 m) of

$$P_{RN} = 316 \text{ kW}$$

The decrease in structural height, however, is not without influence on energy production.

4. Energy output in different locations

Two wind energy plants in two different locations are now to be compared with each other in terms of energy production. Both are designed for a power of P_{RN} = 316 kW. The one design corresponds to the WEC 520, the other to a higher specific installed power of π_N = 400 W/m^2 and a smaller rotor diameter of D = 31.7 m.

In fig. 3, the cumulative frequency H of wind velocities for each location has been plotted. As an example of a region of low wind velocity, the values of the wind measuring station at Stötten on the Swabian Alb have been selected. It is in the vicinity of this station that the WEC 520 prototype is at present being tested. The annual mean value of wind velocity is in this location $\bar{c}$ = 4.5 m/s. For the location with higher wind velocity, Nordeney has been used which has an annual mean of $\bar{c}$ = 7.4 m/s. The values have been published in /2/.

If the frequencies of wind velocity are now processed with the control characteristic curves of the different wind turbine designs as per fig. 2, one obtains as a result the annual energy production of each. In doing so, the respective cumulative frequency curve is sub-divided into intervals for the wind velocity as plotted in fig. 3 for one interval. For the wind velocity on the limits of the interval c_a and c_b the cumulative frequencies H_a and H_b are read off from the respective curve.

$$\Delta h = H_b - H_a \tag{8}$$

for the medium wind velocity c_m of the interval, and from this the absolute frequency

$$f = 8760 \Delta h \, [h/a] \tag{9}$$

From the control characteristic curve of the respective wind turbine (fig. 2), one obtains for the medium wind velocity c_m in the interval a power coefficient c_p with which the power of the wind turbine in the interval is calculated

$$P_R = c_p \cdot \frac{\rho}{2} \cdot c_m^3 \cdot A \qquad (10)$$

The annual energy production is yielded from the summation of the products of power and time over all intervals.

$$E = \sum f_i \cdot P_{Ri} \qquad (11)$$

Naturally, the observation is more accurate the smaller the intervals are selected.

The results for both wind turbines in the different locations are plotted in fig. 4. Shown in the upper part of the figures are the powers achieved by the alternative designs in relation to wind velocity. On the left-hand side of the figure, the relative frequency Δh of the different wind velocities is given for the two locations, Stötten and Nordeney. In the centre of the figure, finally, the anticipated energy production is shwon as a function of wind velocity as well as the anticipated annual energy production as a cumulative value.

In regions of low wind, such as Stötten, one obtains with the WEC 520 with an annual energy of 574 MWh 3.54 times as much energy as would be obtainable from the smaller wind turbine with the same power design. On the North Sea coast, e.g. on Nordeney, the production of 1537 MWh is still almost twice as great (factor 1.94) as that of the smaller plant. If the comparison were made with a plant with non-adjustable rotor blades, the difference would be still greater.

The reason for this lies not only in the higher power coefficient c_p of the WEC 520 at low wind velocities, but also in the fact that the power is dependent upon the square of the rotor diameter (cf. Gl. (1) and (2). Below a wind velocity of c = 12 m/s, therefore, a considerable higher power is provided by the WEC 520 than that of the plant being compared with it (cf. fig. 4 above). Because, however, even in costal areas, the wind blows below this velocity for arount 90 percent of the time (see fig. 3), the higher energy yield is given by the WEC 520.

It should also be pointed out that the rated power of the WEC 520 is reached as early as at a velocity of c_N = 8.7 m/s. At wind velocities higher than this, as e.g. on Nordeney for over 30 percent of the time (see fig. 3), one therefore always obtains the same power delivered. Such a design thus contributes toward a uniformity in the power delivery of a wind energy plant.

5. Possibilities of comparison between different wind energy plants

It is general practice to relate the price of a wind energy plant to the installed power for purposes of comparison. The example described above, however, shows that, according to design, great differences in size of wind turbines can be yielded for the same installed power. With these different designs, one also obtains great differences in annual energy production, although the latter is also dependent upon the location of the plant.The operator, however, is interested solely in energy production, meaning that it is necessary to set the price of plant in relation to its energy yield.

Because the location of a plant is essentially important for the energy yield, two or three wind frequencies would have to be determined as standard values. For these, the annual energy yield would then need to be calculated and set in relation to the price of the plant. Such a possibility of comparison would give the operator a clearer picture of profitability.

A more simple means of comparison is given by setting the square of rotor diameter in relation to the price of a plant. In this way, plants of the same size could then be compared. The energy production, by a more or less good aerodynamic matching of the plant to its location, however, is overlooked in this consideration. Nevertheless, a better scale of evaluation is yielded than by relating the price of a plant to its installed power.

Bibliography

/1/ Betz, A.:   Windenergie und ihre Ausnutzung durch
                Windmühlen
                Vandenhoeck & Ruprecht, Göttingen 1926

/2/ Jarass L.: Windenergie
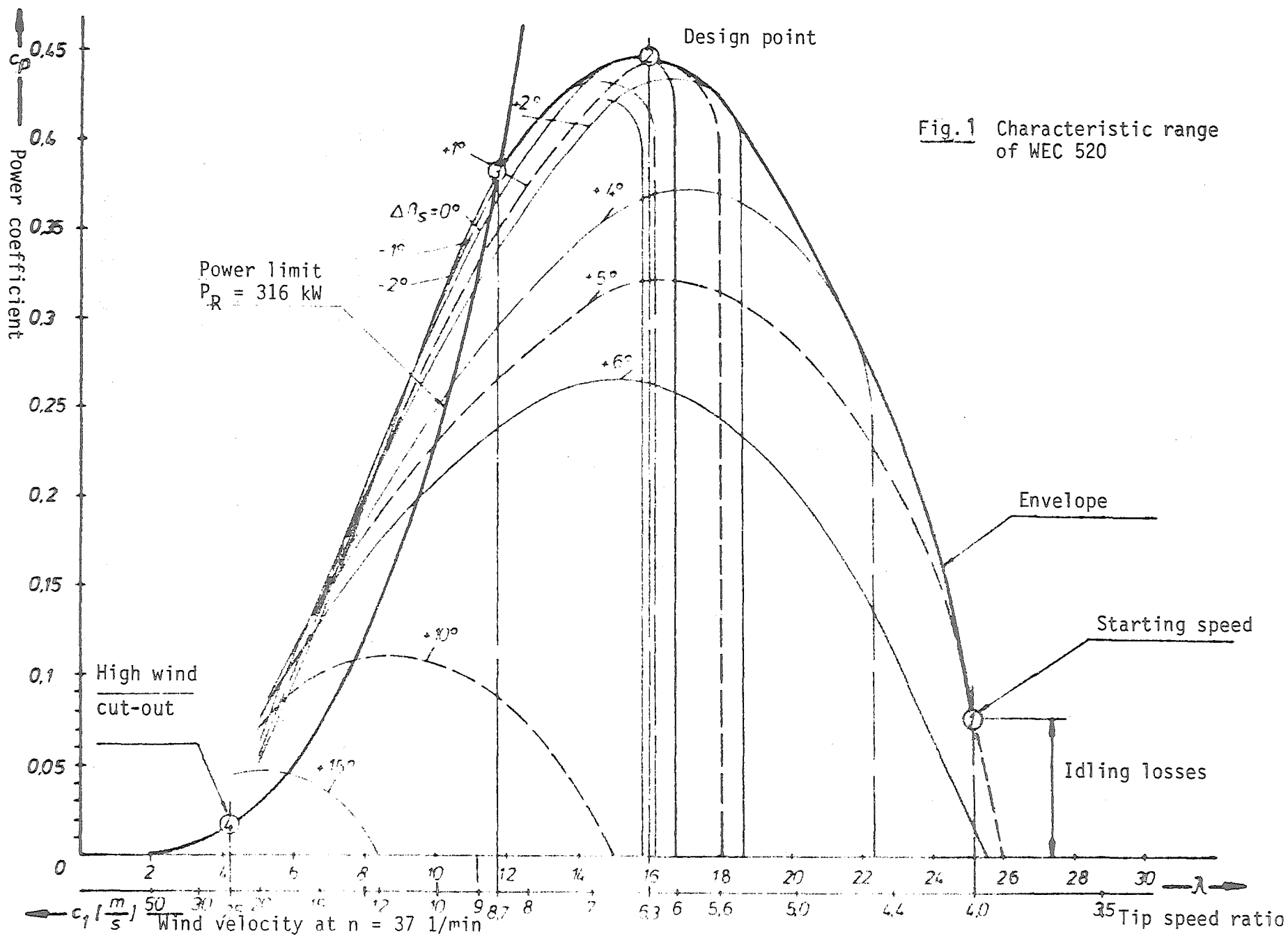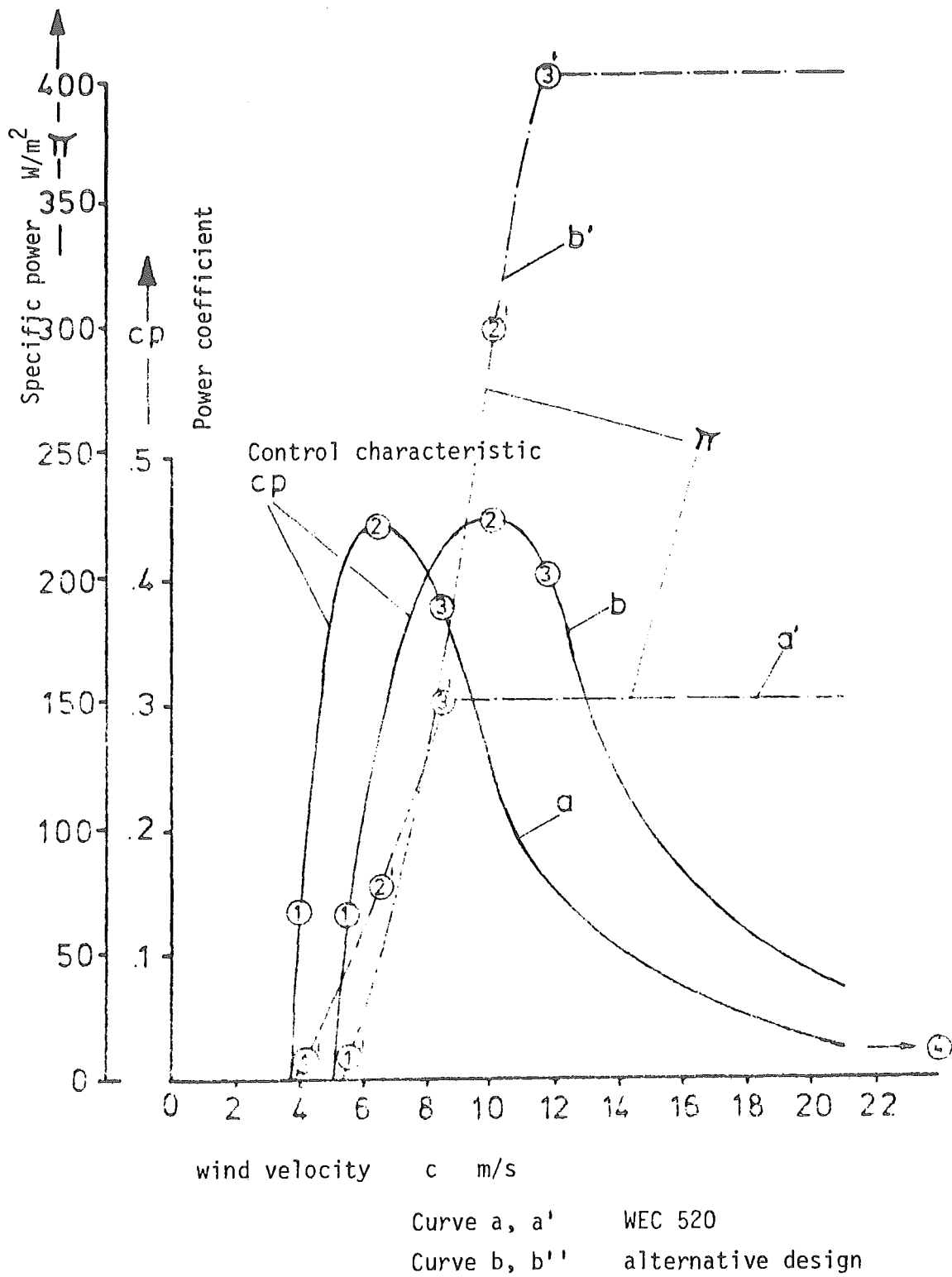   Springer Verlag Berlin, Heidelberg,New York 1980

Fig.1 Characteristic range of WEC 520

Curve a, a'   WEC 520
Curve b, b''   alternative design

Fig. 2   Power coefficient and specific power for two
wind energy converters of different design
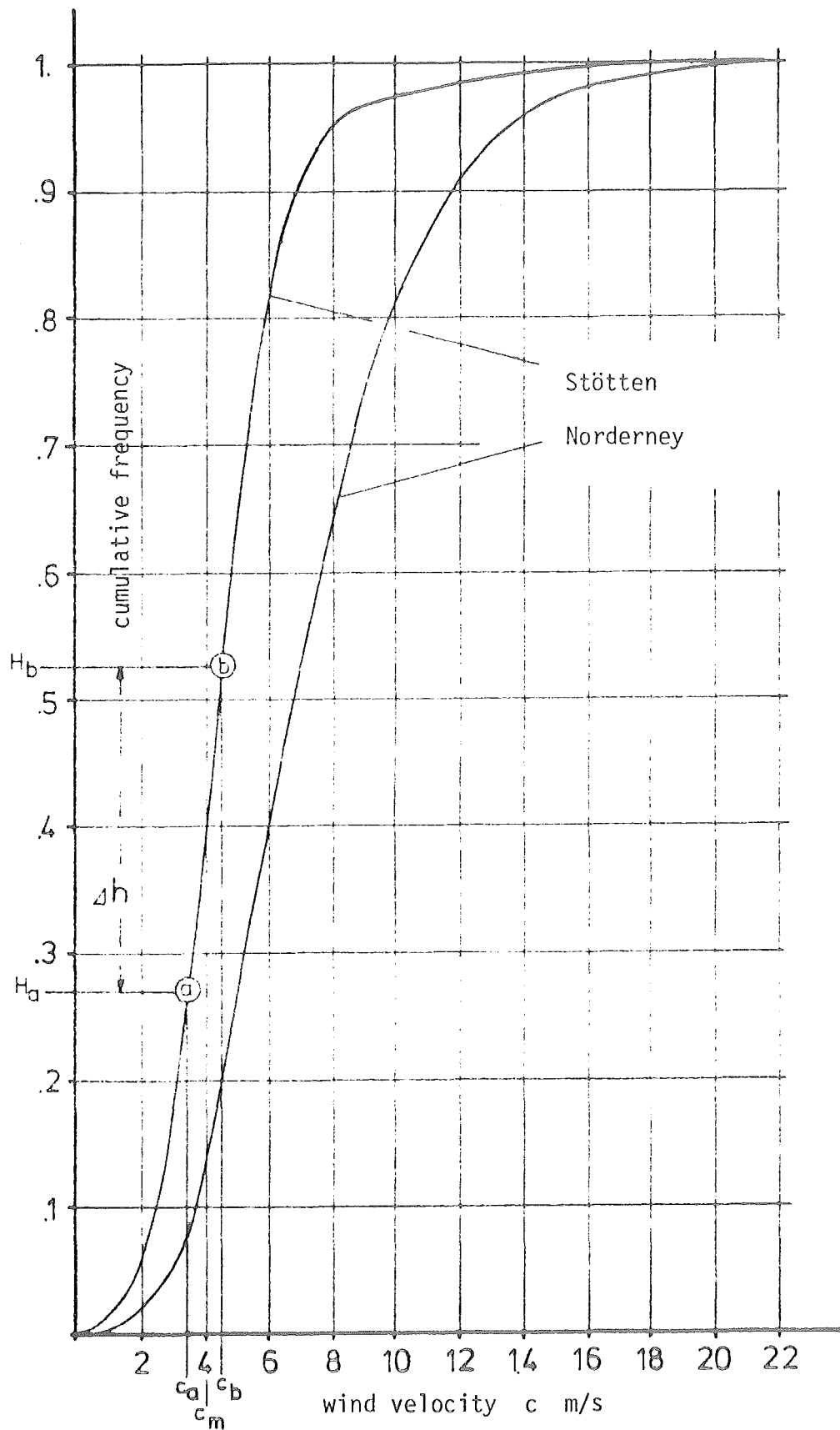
Fig. 3 Distribution of cumulative frequency of wind velocities
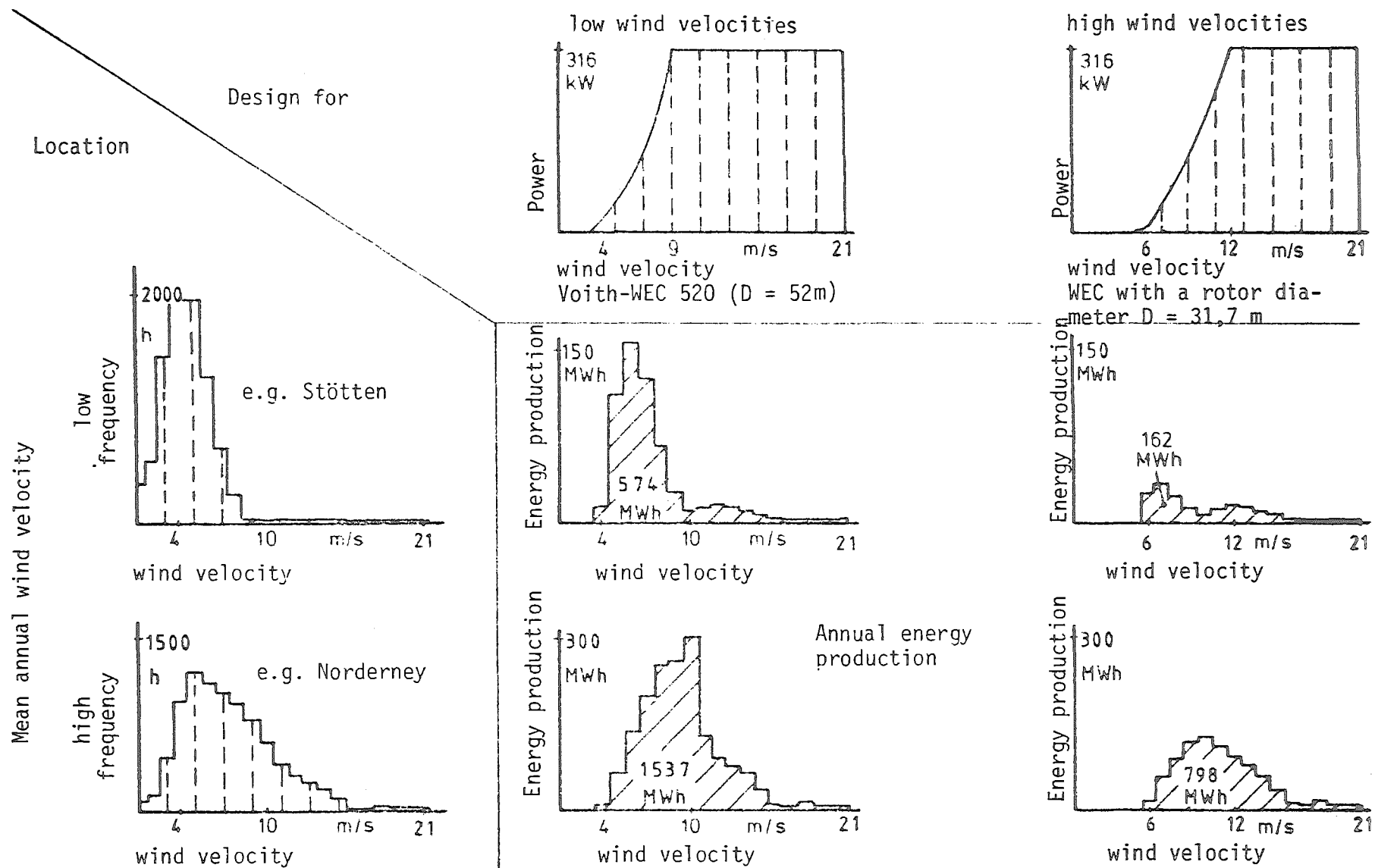
low wind velocities

316 kW

Power

4   9   m/s   21

wind velocity
Voith-WEC 520 (D = 52m)

high wind velocities

316 kW

Power

6   12   m/s   21

wind velocity
WEC with a rotor dia-
meter D = 31.7 m

Design for

Location

Mean annual wind velocity

low frequency

2000 h

e.g. Stötten

4   10   m/s   21

wind velocity

high frequency

1500 h

e.g. Norderney

4   10   m/s   21

wind velocity

Energy production

150 MWh

574 MWh

4   10   m/s   21

wind velocity

Energy production

300 MWh

1537 MWh

Annual energy
production

4   10   m/s   21

wind velocity

Energy production

150 MWh

162 MWh

6   12 m/s   21

wind velocity

Energy production

300 MWh

798 MWh

6   12 m/s   21

wind velocity

216

Fig. 4   The influence of WEC design and location on energy production

RECOMMENDED PRACTICES
FOR WIND TURBINE TESTING

4. ACOUSTICS. MEASUREMENT OF NOISE EMISSION FROM WIND ENERGY CONVERSION SYSTEMS (WECS)

1. EDITION 1984

Edited by

Sten Ljunggren and Anders Gustafsson
FFA, The Aeronautical Research Institute of Sweden
Box 11021, S-161 11 BROMMA, Sweden

and

Andrew R. Trenka
Wind Systems Branch
Rockwell International
P. O. Box 464
Golden, CO 80401, U.S.A.

List of Contents

Introduction

The evaluation of wind turbines must encompass all aspects of a Wind Energy Conversion System (WECS) ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of internationally agreed upon evaluation procedures for each of these areas is needed now to aid in the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the proposed recommendations for wind turbine testing to address the development of internationally agreed upon test procedures which deal with each of the above noted aspects for characterizing WECS. The IEA expert committee will pursue this effort by periodically holding meetings of experts, to define and refine consensus evaluation procedures in each of the areas:

1. Power Performance
2. Cost of Energy from WECS
3. Fatigue Evaluation
4. Acoustics
5. Electromagnetic Interference
6. Safety and Reliability
7. Quality of Power

This paper addresses the fourth item – Acoustics. The expert committee will seek to gain approval of the procedures in each member country through the IEA agreements. The recommendations shall be regularly reviewed and areas in need of further investigation shall be identified.

Scope

This document describes the procedures to be used for the measurement and description of the noise emission of Wind Energy Conversion Systems (WECS).

Field of Application

The major goal of this document is to facilitate comparisons of noise measurements made in different countries by different investigators. The secondary goal is to provide an engineering data base for the development and validation of analytical acoustic prediction techniques.

The document does not address the psycho-acoustic aspect of the acoustic problem, nor does it attempt to define acoustic limits of acceptability for regulatory purposes.

RECOMMENDED PRACTICE FOR MEASUREMENTS OF NOISE EMISSION

1. DEFINITIONS

1.1. A-weighted sound pressure level, L_{pA}, in decibels:

The value of the sound pressure level determined using frequency-weighting network A (see IEC Publication 651). The reference sound pressure is 20 μPa.

1.2. Equivalent continuous sound pressure level, L_{eqT}, in decibels:

$$L_{eqT} = 10 \lg \left[\frac{1}{T_m} \int_o^{T_m} \frac{p^2(t)}{p_o^2} dt \right]$$

where p(t) is the instantaneous sound pressure in pascals

p_o is the reference sound pressure of 20 μPa

T_m is the measurement time interval.

1.3. A-weighted equivalent continuous sound pressure level, L_{AeqT}, in decibels:

The value of the equivalent continuous sound pressure level as defined in 1.2. in which the sound pressure level is determined as in 1.1.

1.4. Reference sound level, $\overline{L_{pA}}$

The mean A-weighted equivalent continuous sound pressure level for the measurement positions at the reference distance R_o, calculated as described in clause 5.1.

1.5. Directivity index, DI_i

The corrected A-weighted equivalent continuous sound pressure level at a measurement position i minus the surface sound pressure level, calculated as described in clause 5.2.

1.6. Lower limiting frequency, f_L, in hertz:

One half of the blade passage frequency;

$$f_L = 0.5 \frac{RPM}{60} n$$

where RPM is number of revolutions per minute of rotor

n is number of blades of rotor.

2. INSTRUMENTATION

2.1. Instruments

2.1.1. Equipment for the determination of the A-weighted equivalent continuous sound pressure level.

This equipment shall meet the requirements of a type 1 sound level meter according to IEC Publication 651. The microphone shall have the maximum diameter 13 mm.

In addition to the requirements for the sound level meter, the equipment shall be capable to provide a read-out of, or otherwise make it possible to obtain the A-weighted equivalent continuous sound pressure level.

If the noise is steady over the period of interest, the measurements may be carried out with equipment that is not capable of registrering the true equivalent continuous sound pressure level. In this case the "slow" response should be used. The reading is taken as the average meter deflection. If the meter reading fluctuates over a range of more than 5 dB, the noise cannot be considered steady.

2.1.2. Equipment for the determination of third-octave band spectra

In addition to the requirements given in clause 2.1.1., the equipment shall have a substantially constant frequency response over at least the frequency range 0.8 Hz to 7100 Hz. The filters shall meet the requirements of IEC Publication 225.

The equipment shall be capable of providing a read-out of the equivalent continuous sound pressure level in third-octave bands with center frequencies from 1 Hz up to 6300 Hz.

Note: More than one measurement and recording system may be necessary to cover the wide frequency and dynamic range of interest.

2.1.3. Equipment for the determination of narrow band spectra

In addition to the requirements given in clause 2.1.1., the equipment shall have a substantially constant frequency response over the frequency range from f_L up to 100 Hz. It shall be capable of providing a read-out of a narrow band analysis with the bandwidth of approximately 0.5 Hz.

2.1.4. Equipment for the determination of filtered instantaneous sound pressure

In addition to the requirements given in clause 2.1.1., the equipment shall contain octave band filters according to IEC 225 with center frequencies from 17 Hz up to and including 1000 Hz. The equipment shall be capable to provide a time history trace of the instantaneous, filtered sound pressure. The time interval should not be shorter than two periods of the rotor.

2.2. Recording of data

When data are stored on tape as an essential step of the measuring procedure, the additional errors caused by the process of storing and replay shall be taken into account when presenting the result of the measurement.

2.3. Windscreen

Microphone windscreens shall be used and appropriate compensation for the effects of its use shall be allowed for in the calibration.

2.4. Calibration

The complete measurement chain must be calibrated at least at one frequency before and after the measurements. An acoustic calibrator with an accuracy of ± 0.5 dB shall be used.

3. MEASUREMENTS

3.1. Measuring positions

Three types of microphone positions are to be used: reference position, key measuring positions and auxiliary measuring positions. These positions shall be laid out in a pattern round the WECS as indicated in Figure 1. The distance from the WECS to each microphone position shall be as indicated in Figure 1 with a tolerance of ± 20%. The reference distance R_0 is for a WECS with a horizontal axis given by:

$$R_0 = H_1 + D_1/2, \tag{1}$$

where H_1 is the distance from ground to centerline of rotor shaft

D_1 is the diameter of the rotor.

For a WECS with a vertical axis the reference distance R_0 is given by

$$R_0 = (H_2 + D_2)/2, \tag{2}$$

where H_2 is the distance from ground to blade upper attachment

D_2 is the equatorial diameter.

The preferred measurement height is 5 m above ground level. It is recommended that the microphone is placed at a distance of at least 2 m from the observer and the rest of the instrumentation.

The measurement position should preferably be chosen so that the influence of reflecting structures (e.g. buildings) is minimized. If this impracticable, a position 1 to 2 m from the reflecting vertical surface may be chosen and the measured value corrected according to clause 6.2.

Note 1: It is acknowledged that the measurement height above ground is an important parameter. Available data indicate strong ground effects at low measurement heights and hence a measurement height of 5 m is suggested to avoid ground effects. This recommendation may be changed later when more experience is available. A measurement height of 1.2 m may, however, be used as an alternative. In such a case simultaneous measurements at 5 m height should be performed at one position.

Note 2: Different techniques to minimize the influence of background noise are developing and improved technique can be expected in the near future. The recommendations stated here may therefore be changed later.

3.2. Acoustic measurements

3.2.1. A-weighted equivalent continuous sound pressure level

The A-weighted equivalent continuous sound pressure level shall be determined in all of the measuring positions and as near as practical to rated wind speed and power.

The A-weighted equivalent continuous sound pressure level shall also be determined at the reference position for the following WECS operating conditions:

a) above rated power (near maximum wind condition),

b) shut down (high wind condition, if possible),

c) WECS parked (background measurement; if possible also before erection). These measurements should be taken at the same windspeeds as the measurements of the noise emission.

Each measurement is recommended to be at least 2 minutes in duration where practicable and under periods of steady wind. Remarks on subjective impression of noise (audible discrete tones, impulsive character, spectral content, temporal characteristics, etc.) shall be noted.

3.2.2. Measurements at the key measuring positions

In addition to the measurement of the A-weighted continuous sound pressure level, the following quantities shall be determined at one or more of the four key measuring positions:

a) the equivalent continuous sound pressure level in third-octave bands with center frequencies from 1 Hz up to 1000 Hz,

b) a time history trace of the instantaneous sound pressure filtered through octave band filters with center frequencies from 16 Hz up to and including 1000 Hz,

c) narrow band spectrum for the frequency range f_L to 100 Hz, obtained with a bandwith of approximately 0.5 Hz.

It is recommended that these quantities are obtained for the same time interval and that the measurements are carried out simultaneously at the four measuring positions.

When use is made of tape recording, the duration of the record should be made long enough to achieve what is prescribed above.

These measurement shall be made at or near rated wind speed and power output conditions of WECS and under the same wind conditions with the WECS parked (background conditions).

Notes:

1) Whenever possible, the measured signals should be recorded on magnetic tape for control and reference purposes. It must, however, be borne in mind that even for high-quality tape recorders, the dynamic range is fairly restricted as compared to the instruments described in clause 4.1.

2) In most field measurements it is desirable to use headphones or suitable peak overload detectors to detect the onset of overload or distortion of the measuring system.

3) Wind turbine noise and wind generated background noise are known to vary, even at apparently constant wind speeds. Thus, an assessment of these variations is valuable, e.g., in terms of time distributions of the octave band levels. Additional recommendations to cover this point may be made later.

3.3. Non-acoustic measurements

During the measurements specified in clause 3.2. the following WECS related parameters shall be continuously recorded:

* wind speed and direction at hub height (or if measured at any other height, corrections to hub height shall be consistent with reference [3]),
* WECS power output,
* rotor RPM,

and optionally also

* blade pitch angle,
* WECS yaw position.

Also to be recorded every ½ hour are:

* humidity,
* temperature,
* barometric pressure,
* turbulence (qualitative assessment). If equipment to measure the turbulence is not available, the following parameters shall be reported: time of day, cloud cover and terrain type. The turbulence can then be estimated approximately from these parameters together with windspeed,
* the possible presence of a temperature inversion in the atmosphere.

4. CORRECTIONS

The corrections in this clause only apply to the measured values of the A-weighted equivalent continuous sound pressure level.

4.1. Background level

The A-weighted equivalent continuous sound pressure level shall be corrected for the influence of background noise according to table 1.

Table 1 – Correction for background noise

Difference between sound pressure level with WECS operating and background sound pressure level alone	Correction to be subtracted from sound pressure level measured with WECS operating to obtain sound pressure level due to WECS alone
3	3
4-5	2
6-9	1
≥10	0

4.2. Reflexions

3 dB shall be subtracted from the values obtained near a vertical reflecting structure.

5. DERIVED RESULTS

5.1. Reference sound level

The reference sound level, $\overline{L_{pA}}$, is to be calculated from the measured values of the A-weighted equivalent continuous sound pressure level L_{pi} at the reference distance R_o (after corrections are applied according to 4.1. and 4.2., if necessary), by using the following equation:

$$\overline{L_{pA}} = 10 \lg \left[\frac{1}{\sum\limits_{i=1}^{N} \Delta\varphi_i} \sum\limits_{i=1}^{N} \Delta\varphi_i \left(\frac{R_{oi}}{R_o}\right)^2 10^{0.1 L_{pi}} \right] , \quad (3)$$

where $\overline{L_{pA}}$ is the reference sound, level, in decibels,

    $\Delta\varphi_i$ is the angle represented by position no i (between 15° and 30°, see Figure 1),

    R_o is the reference distance according to Eq. (1) or (2),

    R_{oi} is the actual distance for location i ($R_o \pm 20\%$),

    L_{pi} is the A-weighted equivalent continuous sound pressure level resulting from the measurement at position no i, see Figure 1,

    N is the number of measurement points at the reference distance R_o.

5.2. Directivity index

The directivity index, DI_i, is to be calculated from the measured values of the A-weighted equivalent continuous sound pressure level L_{pi} at the actual distance R_{oi} (after corrections are applied according to 4.1. and 4.2., if necessary) and the surface sound pressure level, by using the following equation:

$$DI_i = L_{pi} - \overline{L_{pA}} + 20 \lg \frac{R_{oi}}{R_o} , \quad (4)$$

where DI_i is the directivity index for the position i,

    L_{pi}, $\overline{L_{pA}}$, R_{oi} and R_o are as in clause 5.1.

6. ADDITIONAL INFORMATION TO BE RECORDED

6.1. Characterization of the WECS

The WECS geometric configuration and its operating conditions must be completely characterized. The WECS configuration should be described in detail and should include such descriptors as hub height, rotor configuration, tower configuration, dimensions and geometry of the rotor including its diameter, number of blades, planform, overspeed controls, fixed or variable pitch blade angle, teetering rotor, yaw configuration, generator type, geartooth frequency, etc.

6.2. Acoustic environment

The following information on the acoustic environment at and near the site of the WECS and the measuring positions shall be recorded:

a) type of topographic terrain (hilly, flat, cliffs, mountains, etc., for nearest 1-2 km). Photographs should be included,

b) type of ground (grass, sand, etc.),

c) nearby reflecting structures such as building structures and sound sources such as trees, bushes, water surfaces, etc.,

d) other nearby sound sources such as highways, industrial complexes, airports etc., which may affect the background level.

6.3. Instrumentation

- The equipment used for the measurements, including name, type, serial number and manufacturer,
- frequency response of instrumentation system,
- bandwith of narrow band frequency analyzer.

6.4. Acoustical data

- The locations and orientation of the microphone at each measurement position.
- The corrections in decibels, if any, applied in each frequency band for the frequency response of the microphone, frequency response of the filters in the pass band, background noise, etc.
- The reference distance R_0.

7. INFORMATION TO BE REPORTED

In addition to the data specified in clause 3 and 6, the following information should appear in the test report:

a) **Identification of WECS**

The test report should contain a complete description of the WECS which was tested. Information to be included would be a description (and if appropriate, a diagram) of the appearance of the wind turbine, its conventional operating characteristics, and the performance characteristics of the machine which may relate to noise.

b) **WECS operating procedure**

A description of how the WECS is operated under test is an essential part of the report. If the machine is operated in any manner other than its conventional operating mode, this operating procedure should be completely described.

c) **Acoustical data**

The Reference sound level and the directivity index rounded to the nearest whole decibel the corrections applied.

d) **Measurement uncertainty**

The section on measurement uncertainty should give some indication of the degree of confidence which can be placed in the measurement results. This could be expressed in terms of standard error, confidence limits, or some other appropriate statistical factor.

e) **Time and date**

Time and date when the measurements were performed.

8. ACKNOWLEDGEMENT

This document has been developed through a series of meetings with participants from different countries participating in the IEA R/D-agreement. The following persons have participated with valueable contributions at these meetings

S. Söderqvist, Sweden
M. Hedegaard, Denmark
A. Robson and P. T. Manning, United Kingdom
A. de Bruijn and L. van Schie, The Netherlands.

Valuabale written comments have also been obtained from N. D. Kelley and D. G. Stephens, U.S.A. and S. A. Glegg and S. J. Elliott of United Kingdom.

9. REFERENCES

[1] IEC Publication 225-1966. Octave, halv-octave and third-octave band filters intended for the analysis of sound and vibrations.

[2] IEC Publication 651-1979. Sound level meters.

[3] Expert Group Study on Recommended Practices for Wind Turbine Testing & Avaluation: 1. Power Performance Testing; Edited by Sten Frandsen; B. Maribo Pederson; Andrew R. Trenka, submitted to the Executive Committee (the International Energy Agency Programme for Research & Development on Wind Energy Conversion Systems). Edition 1982.
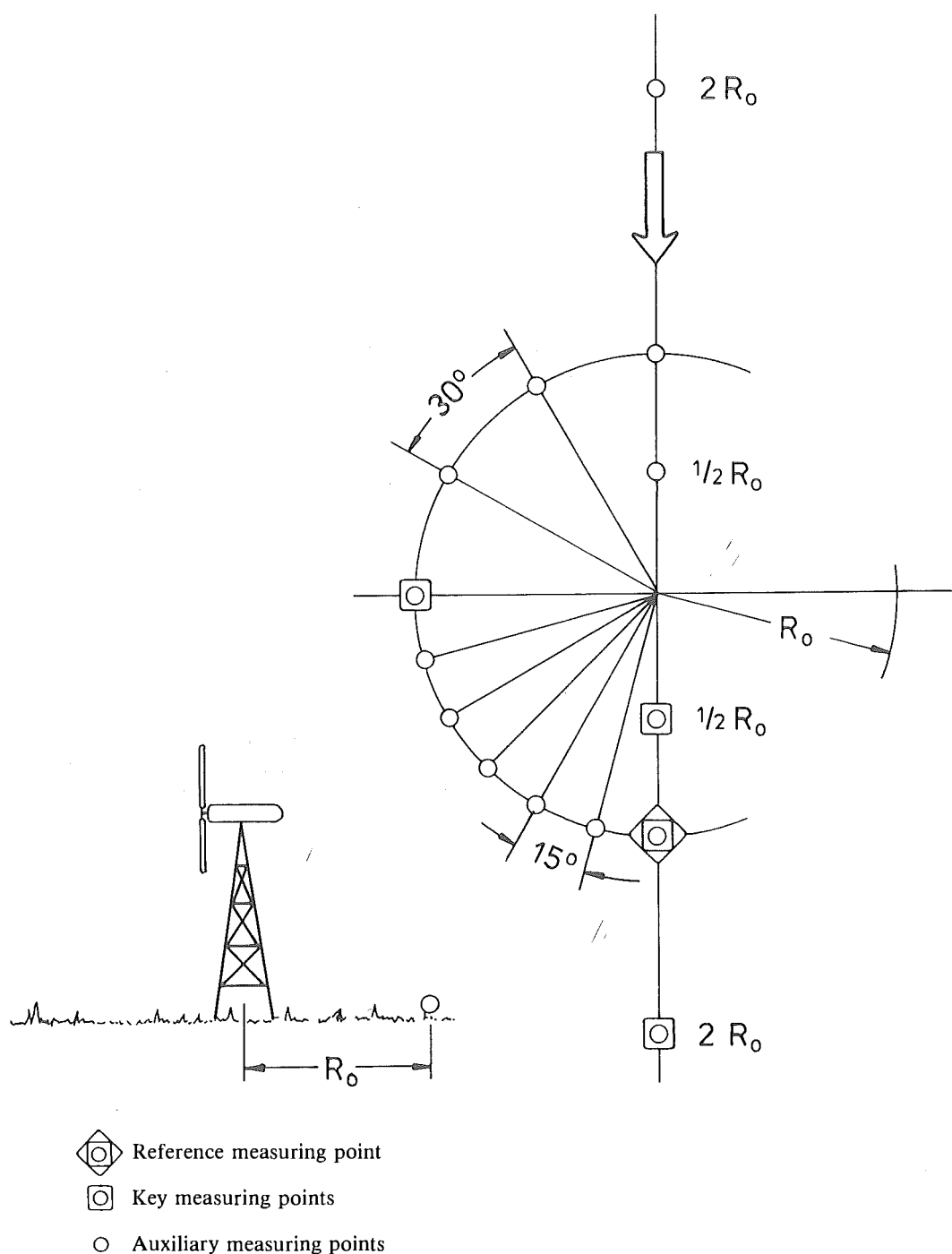
Figure 1. Recommended pattern for measuring points.

Available on request from:

B. Maribo Pedersen
Dept. of Fluid Mechanics
Technical University of Denmark
Building 404
Lundtoftevej 100
DK-2800 Lyngby
Denmark

H. J. M. Beurskens
ECN
Westerduinweg 3
Postbus 1
NL-1755 ZG Petten
The Netherlands

D. F. Warne
ERA Technology Ltd.
Cleeve Road
Leatherhead
Surrey
England

A. R. Trenka
DOE/USA
Rockwell International
P.O. Box 464
Golden
Colorado 80401
USA

A. Gustafsson
FFA
Box 11021
S-1611 11
Sweden

Concluding remarks from general discussion on May 8, 1984

at IEA LS WECS Expert meeting on environmental aspects on
Large Scale Wind Energy Utilization

Visual impact

Even if it is essential to make a good visulization of a
future WECS installation when plans are presented the
reaction of the public towards the visualisation and towards
the following real installation may not be indentical.

The impression of rotating real machines is very difficult
to visualize with pictures of non rotating machines. E.g.
example at Palm Springs, where further installation plans had
to be altered due to unfavourable reactions after the initial
installation, despite the full plans had been thoroughly
presented before (Andy Trenka).

Noise

Noise may become the most decisive siting parameter.

Tip speed is the singel most important parameter (Staffan
Meijer).

The background noise level is very important. At the North of
Scotland Hydro Electric Board Wind turbines, the difference
between turbine noise and background noise is 15 dB at the
machines, but only 5 dB at 150 m distance, which is hardly
perceivable. The NSHB has taken several readings of back-
ground noise and concluded that the increase in level is
typically 2.5-3 dBA per m/s of wind speed (Bill Stephensson).

It is essential to further develop measurement techniques
for background wind noise to avoid "pseudo" noise in micro-
phones etc. A special workshop on this subject ought to be
arranged (Robson) (Later decided to be held in Sweden during
fall 1984).

There was a general understanding that existing noise regu-
lations have to be supplemented for background wind noise. In
Holland there will be recommendations on background noise
levels for determining allowable wind turbine noise within a
year (de Kuypers).

Safety

There was a general understanding that the theory behind
eventual blade throw distances was thoroughly investigated
and that no further principal work - including experiments -
was needed. If and when a blade throw accident occurs the
relevant parameters for verification of calculations ought to
be registered (Windheim). Some of the bigger machines might
have data acquisition systems suitable for this.

The difficulties to discuss risk levels with non-profession-
als was underlined. From psycological reasons it might be
better to emphasize that every possible means in order to
minimize the risk of a blade failure is made - which indeed
is true - rather than to outline the very low risk even if
something happens.

The acceptable risk level depends very much on the indi-
vidual. A common value of an acceptable risk level for the
society is 10^{-7} fatalities per person and year. For an indi-
vidual the value often is a factor ten higher (Robson).

A 'safe-life' philosophy accompanied by frequent inspections is the proper way (de Kuypers).

Birds

There was a general understanding that possible bird kills do not seem to present any major problem.

Due to new roads being built to the wind turbine sites, and therefore more human disturbance, the nesting pattern might be disturbed. Investigations are under way. The policy should be to try to keep visitors within small areas (Bill Robinsson).

Nesting investigations at the Swedish prototype sites have revealed a slight increase in the bird population, due to the attraction to birds that use manmade structures for nesting (Staffan Engström).

Even if bird kill and disturbance does not seem to present a problem, great caution has to be made before siting windmills in internationally classified bird areas (Maribo Pedersen).

Lightning

The Maglarp wind turbine has received about ten lightning hits in nine months, which is more that anticipated. The countermeasures taken however seem to have protected the turbine, with one exception. The current design of the aluminium foil lightning protection on the blades needs some maintenance for repair of burns after lightning strikes and especially due to aerodynamic wear (Mats Agrell).

Lightning protection aluminium tape on fibre-glass blades might work better if it is not covered by painting.

It is not known whether there have been lightning strikes on the Growian. The measuring masts might have protected it. In a nearby mast 100 strikes a year have been received (Zwar).

The old Nibe blades have a conventional lightning protection system, However, the Nibe B all wooden blades have no lightning protection, as is the case with all small Danish wind turbines (Maribo Pedersen).

Icing

No ice on blades have been observed at Maglarp, despite numerous ice alarms and ice on rails etc. Wind direction indicators (unheated) have frozen and stuck on several occasions. (Mats Agrell)

In the 82-83 season heavy icing occured on the stationary Growian blades. Personel had to be protected from falling ice by a wooden roof (Zwar)

TV-interference

The cost to avoid to intercrease was found to be substantial in some cases and might hence be a determining factor for site selection (Stephensson).

According to decision by court, there is no right for undisturbed TV-reception in Germany (Zwar).

P A R T I C I P A N T S

Agrell, Mats	Sydkraft, Sweden
Banzhaf, Hans-Ulrich	Voith, Germany
Brinkmann, Inger	Environmental Protection Board, Sweden
Engström, Staffan	National Energy Administration, Sweden
Ernst, Helmut	Lahmeyer International, Germany
Gustafsson, Andes	Aeronautical Research Institute, Sweden
Hau, Erich	MAN-NT, Germany
Henke, Lüder	Lahmeyer International, Germany
Isenberg, Gerhard	MAN-NT, Germany
Körber, Friedrich	MAN-NT, Germany
Kuipers, Joop	KEMA, Netherlands
Meijer, Staffan	Aeronautical Research Institute, Sweden
Möller, Lars	KFA Jülich - PLE, Germany
Pedersen, B. Maribo	Technical University of Denmark
Rasmussen, Søren	National Agency for Physical Planning, Denmark
Robson, Anthony	CEGB, United Kingdom
Sørensen, Göran	Swedish State Power Board, Sweden
Stevenson, W.G.	NOSHEB, United Kingdom
Trenka, Andrew R.	Rockwell International, USA
Windheim, Rolf	KFA Jülich - PLE, Germany
Zwahr, Heiner	GROWIAN-Company, Germany

IEA Implemeting Agreement LS-WECS

Previous Expert Meetings

1. Seminar on Structural Dynamics, Munich, October 12, 1978 (out of print)

2. Control of LS-WECS and Adaptation of Wind Electricity to the Network, Copenhagen, April 4, 1979

3. Data Acquisition and Analysis for LS-WECS, Blowing Rock, North Carolina, Sept. 26-27, 1979

4. Rotor Blade Technology with Special Respect to Fatigue Design Problems, Stockholm, April 21-22, 1980

5. Environmental and Safety Aspects of the Present LC WECS, Munich, September 25-26, 1980

6. Reliability and Maintenance Problems of LS WECS, Aalborg, April 29-30, 1981

7. Costings for Wind Turbines, Greenford, March 7-8, 1983

8. Utility Operating Experiences and Issues with Large-Scale Wind Energy Utilisation, Palo Alto, October 13-14, 1983

9. Structural Design Criteria for LS WECS, Greenford, March 7-8, 1983

10. Utility and Operational Experiences and Issues from Major Wind Installations, Palo Alto, October 12-14, 1983

11. General Environmental Aspects of Large Scale Wind Utilisation Munich, May 7-9, 1984

12. Aerodynamic Calculational Methods for WECS. To be held in Copenhagen, October 29-30, 1984