WIND TURBINE ICING - ITS IMPLICATIONS FOR PUBLIC SAFETY

E A Bossanyi and C A Morgan
Garrad Hassan and Partners Limited
Coach House, Folleigh Lane
Long Ashton
Bristol BS18 9JB
United Kingdom
Tel. +44 1275 394360
Fax. +44 1275 394361
Email. bossanyi@garradhassan.co.uk
Email. morgan@garradhassan.co.uk

ABSTRACT

Developers and owners of wind turbines have a duty to ensure the safety of the general public and their own staff. However, there are currently no guidelines for dealing with potential dangers arising from ice thrown off wind turbines. This puts developers, owners, planning authorities and insurers in a difficult position. To rectify this situation, the work presented here has commenced in order to produce an authoritative set of guidelines. Initial work has resulted in the development of a risk assessment methodology which has been used to demonstrate that the risk of being struck by ice thrown from a turbine is diminishingly small at distances greater than approximately 250 m from the turbine, in a climate where moderate icing occurs.

KEYWORDS: Icing/Frost; Safety; Public Attitudes, Perceptions/Acceptability.

1 INTRODUCTION

The work presented here is being undertaken as part of a project entitled "Wind Energy in Cold Climates (WECO)" part-funded under Joule contract JOR3CT950014 of DGXII which runs for 1996-98. This project is being co-ordinated by the Finnish Meteorological Institute with DEWI (D), Garrad Hassan (UK), Risø (DK) and VTT (FI) as contractors. The project also involves associate contractors and subcontractors from many other European countries. The WECO project has three central objectives, to:

- Refine current assessments of the European wind energy resource through development of ice maps for the constituent countries.
- Identify methods for the improvement of the performance of wind turbines and anemometry technology in ice-prone climates and to quantify the cost implications of these methods.
- Produce safety guidelines for wind developments in ice-prone areas

The work presented here addresses the last of these and has been motivated by an absence of authoritative reference material on the subject when it is raised as a concern by planning authorities and neighbours to proposed wind turbine developments. The lack of previous work on the subject may reflect the fact that there has been no reported injury from ice thrown from wind turbines, despite the installation of more than 2000 MW of wind energy world-wide. In addition, relatively few turbines have been installed in climates where icing is a serious problem. That situation is rapidly changing as extensive development of the wind resource in many Northern European countries has now commenced. Indeed, the potential risk has recently attracted significant publicity in Germany.

2 FORM OF PROPOSED GUIDELINES

On completion of the work being carried out in WECO on this subject, guidelines will be proposed for the treatment of the potential risk to public safety resulting from ice throw. It is proposed that these guidelines will serve as a reference source for wind energy developers and operators, planning authorities and turbine suppliers. They will include:

- A factual explanation of the risk and presentation of observed occurrences of ice throw.
- Description of a methodology for calculating ice throw and consequent risk. Presentation of risk for a wide area around the turbine, for various scenarios of turbine configuration and for a range of fragment sizes and icing scenarios.
- A list of suggested preventative measures for any situations where a significant safety risk is predicted.

3 OBSERVATIONS OF ICE THROW

A key component in the production of guidelines is a sound basis of observed data. For ice-throw, the only substantive data are those collected in the recently completed EU Joule project "Icing of wind turbines", also funded by DGXII. As part of this work, carried out by DEWI and FMI, a questionnaire was circulated to a large number of turbine operators as described by Seifert [1]. The questionnaire asked for information on the occurrence of icing including mass and location of any observed ice debris flung off the rotor. The distribution of this questionnaire will continue as part of the WECO project.

Figure 1 summarises the data collected so far, as supplied by DEWI [2]. The data presented in Figure 1 show that most fragments which were found on the ground were estimated to be in the range 0.1 to 1 kg mass and were found 15 to 100 m from the turbines. Of course these figures must be taken as very approximate, and it is not possible to know how well the ground was searched especially at larger distances from the turbines.

In addition to the results gathered by the questionnaire, anecdotal evidence suggests that the tendency is for ice fragments to be dropped off, rather than thrown off, the rotor. Also, it tends to be shed off the tips in preference to other parts of the blade and large pieces of debris tend to fragment in flight. There is significant evidence that rime ice continues to form when the turbine is operating and is not shaken off by blade flexing, even though this may be the case for other types of ice formation. Also, rime ice formation appears to occur with remarkable symmetry on all turbine blades with the result that no imbalance occurs and the turbine continues to operate.

4 MODELLING OF ICE THROW

4.1 Aspects to be modelled

The risk of a person being hit by a fragment of ice thrown from an operational wind turbine depends on the following factors:

- The probability of the turbine having ice build-up on the blades
- The likelihood of ice fragments becoming detached from the blade, which is undoubtedly a function of radial position on the blade and on blade azimuth. It may also depend on the speed of rotation of the blades, as well as on blade pitch, blade profile and flexibility.
- The point where the detached ice fragment lands, which also depends on the radial position and azimuth at the time of becoming detached, and on the rotor speed and wind speed. The speed of the fragment at the end of its trajectory is also of interest, and this depends on the same factors.
- The probability of the person being in an area of risk and any safety precautions taken.

4.2 Method for ice throw trajectory prediction

While little is known about the probability of ice fragments becoming detached from various parts of the blade, it is relatively easy to calculate the distance travelled and the final velocity of the fragment once it has become detached, assuming that it does not break up in flight. A method for doing this has been developed as part of WECO and has been previously described by the authors [3]. This model has been further developed and now includes modelling of the effect, on the trajectory, of:

- Blade azimuth at the instant when the fragment is released
- Radial location of the fragment on the blade at the instant of release
- Any radial sliding velocity developed by the fragment prior to release (slingshot)
- Turbine dimensions and rotor speed
- Gravity
- Fragment dimensions
- Aerodynamic drag
- Aerodynamic lift
- Mean downstream wind speed

To demonstrate the application of this model, the trajectories of ice fragments have been calculated as a function of initial position, which is defined as the radial and azimuthal position at which the ice became detached from the blade. Calculations have been carried out with the parameters shown in Table I.

Radius of turbine	25	m
Hub height	40	m
Rotor speed	25	rpm
Release radial velocity	0	m/s
Wind speed	13	m/s
Ice fragment mass	1	kg
Ice fragment drag area	0.01	m^2
Drag coefficient	1.0	
Ice fragment lift area	0.01	m^2
Lift coefficient	0	
Air density	1.225	kg/m^3

Table 1 Base-line parameters for ice throw calculations

Figure 2 shows a contour plot of the range, defined as the total distance from the tower base at which the fragment reaches the ground, as a function of initial position on the rotor, without the slingshot effect. The final speed, defined as the speed of the fragment when it hits the ground, is shown in a similar contour plot. The rotor is turning anti-clockwise on these plots, and clearly the greatest range (nearly 200 m) is achieved by fragments leaving the tip of the rising blade when the azimuth is approximately ±45° from the horizontal. The greatest landing speed (approaching 60 m/s) is achieved by fragments leaving the tip of the falling blade when roughly in the horizontal position, although for most parts of the rotor the landing speed is less than 40 m/s. Note that for the assumed ice fragment size and weight, the terminal velocity, when drag and gravity forces are in balance, is almost exactly 40 m/s.

4.3 Sensitivity studies

Some sensitivity studies were carried out using this model to demonstrate the importance of aerodynamic drag, aerodynamic lift, fragment mass, slingshot, turbine parameters and wind speed. Calculations were performed for the case of detachment occurring at the blade tip at an azimuth of 135° from bottom dead centre on a rising blade. Sensitivity was determined in each instance by an individual perturbation from the base case which is summarised in Table 1.

4.3.1 Aerodynamic drag

It was found that ignoring the effect of drag completely increased the range by a factor of approximately 3 and the landing speed by a factor of 2. However, the range and landing speed are relatively insensitive to the exact value of aerodynamic drag coefficient. A doubling of the drag coefficient (or of the fragment drag area) when compared to the base case gives a reduction of only 29 % in the range. This result also gives a guide to the sensitivity to fragment size and hence, for a given mass, ice density.

It is important to note that aerodynamic drag not only slows the ice fragment down, which reduces the range: it also causes the fragment to be swept downwind, which increases the range. Clearly at higher wind speeds the fragments would be swept still further downwind.

4.3.2 Aerodynamic lift

As ice fragments are irregular in shape, their flight is most likely to involve tumbling motion and the assumption of zero lift is likely to be a quite accurate for the trajectory as a whole. When lift does occur it can be either positive (upwards) or negative (downwards). If the net lifting forces throughout the trajectory give an average lift coefficient of -1.0, the range reduces by 25 %. Surprisingly, if the average lift coefficient is +1.0, the range is also reduced because the fragment gains height, loses momentum and then plummets. An average lift coefficient of +0.25 was found to maximise the range, with a 1 % increase on the base case. A greater relative increase in the range resulting from upwards lift forces will occur when the initial velocity vector is rather closer to the horizontal.

4.3.3 Fragment mass

With ice density as in the base case, the fragment mass is proportional to the size (volume) of the fragment. It was found that range is relatively insensitive to fragment mass with a 50 % reduction in mass from the base case giving a 29 % reduction in range.

4.3.4 Slingshot

The effect of slingshot can possibly be caused by acceleration of the fragment along the blade prior to its release from the rotor. This results in the fragment having a radial velocity component at release. It was found that by assuming the fragment slid along the blade from root to tip before release with a velocity vector at 45° to the horizontal, the range increased by approximately 45 %.

4.3.5 Turbine parameters and wind speed

Figure 3 shows the sensitivity of the range and final velocity to turbine radius (assuming no change in tip speed), tower height, rotor speed (and hence tip speed, since the turbine radius is fixed), and wind speed. Once again, the ice is assumed to become detached from the blade tip at an azimuth of 135° from bottom dead centre on a rising blade. Not surprisingly, the tip speed is far more important than the rotor diameter or tower height. Wind speed is also clearly an important parameter. The reference case has a tip speed of about 65 m/s, and the range increases from about 175 m at 13 m/s to nearly 200 m at 25 m/s.

4.4 Risk assessment

The above calculation methods have been extended to make estimates of the probability of any particular ice fragment landing in a given square metre area of ground. This is considered to be representative of the risk of a person standing in one particular point being struck. In the absence of field data, an assumption is required on the relative probability of the ice fragment becoming detached as a function of its radial position on the blade, and the azimuthal position of the blade. The following assumptions have been made:

- The fragment is equally likely to become detached at any blade azimuth angle.
- The probability of ice detachment at the tip is three times greater than at the hub, with linear interpolation used for other radial positions.
- Ice fragments have properties as in the base case shown in Table 1 except that for each flight the lift coefficient is set to a value drawn from a triangular probability distribution centred on zero with extremes of ±1.0. The fragment mass is determined by assuming that any mass in the range 0-1.5 kg is equally likely.
- Wind speeds are distributed according to a Rayleigh distribution with a mean of 8 m/s, and there is no correlation between wind speed and the occurrence of icing conditions. This latter assumption is considered conservative.
- Turbine nacelle is aligned with the wind.
- Rotor radius is 25 m, hub height 40 m, rotational speed 25 rpm when the wind speed is between 5 and 25 m/s.
- The rotor speed is zero when the wind speed is outside the range 5 to 25 m/s.
- Slingshot has a 10 % probability of occurring for any release.
- A total mass of 400 kg of ice is shed per year. This is an estimate of the ice built up on a turbine experiencing rime ice conditions for 5 days per year,

based on recent observations on upland UK wind farms.

A Montecarlo analysis of 10,000 fragment releases has been used and the ranges of the fragments binned to obtain the distribution of landing probability per unit ground area.

The results of the Montecarlo analysis are shown in Figures 4 and 5 which represent the number of ice fragments landing on any one square metre of ground area in a year, as a function of distance from the turbine and as plan view format, respectively.

From these results it would appear that outside the area directly underneath the rotor, the risk of being hit by ice fragments drops away very rapidly with distance. At a distance of 250 m the risk is approximately 10^{-5} for the scenario assumed in this simulation. This is comparable to a figure, quoted by MacQueen [4], for the probability of one square metre of ground area being struck by lightning, of 10^{-6} per year in the UK.

The risk figures calculated do not allow for any action taken by those at risk to reduce the danger. MacQueen quotes the example of people taking shelter in lightning storms which results in the risk of people being struck by lightning having a value of 10^{-7}. Similarly, people are likely to avoid exposed wind farm sites in icy conditions which may reduce the risk to a similar level.

Figure 5 shows that the risk is very much concentrated in the rotor plane and just behind it. Service personnel can therefore reduce the risk of injury significantly by simply by staying slightly upwind of a turbine, provided any other turbines upwind are more about 150 m away, as is likely to be the case for large wind turbines.

5 CONCLUSIONS

The methodology which has been presented here for the prediction of ice throw and risk has lead to some interim findings:

- At distances of greater than 250 m, the risk of an area being struck by fragments of ice cast off a wind turbine is comparable to the risk of a lightning strike.
- This risk is largely dictated by the rotor tip speed and the amount of ice which is shed. To state the obvious - where turbine icing does not occur, no risk exists.
- The risk is relatively independent of turbine size and configuration and the aerodynamic properties of the fragments.
- There are limited observed data which are consistent with the ice throw predictions presented here. Further data should result from future responses to the WECO icing questionnaire.

6 REFERENCES

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7 ACKNOWLEDGEMENTS

The work presented here has been part-funded by the European Union under the DGXII Joule programme, contract JOR3-CT95-0014, and by ETSU for the UK Department of Trade and Industry. The authors would also like to thank Henry Seifert of DEWI for supplying observed data.

FIGURES

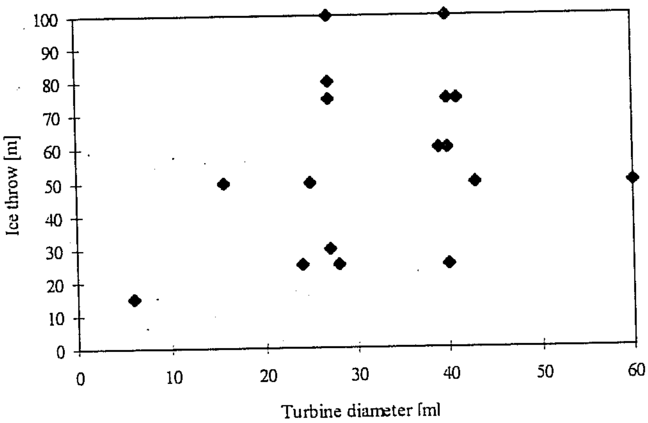

Figure 1: Ice throw data collected by icing questionnaire

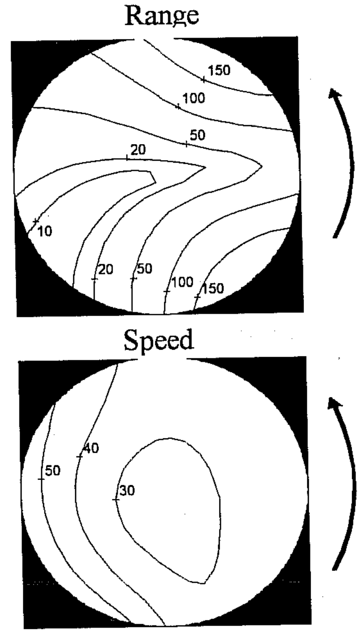

Figure 2: Range and final speed contours for an ice fragment as a function of initial position on rotor disc: 50m diameter, no slingshot effect

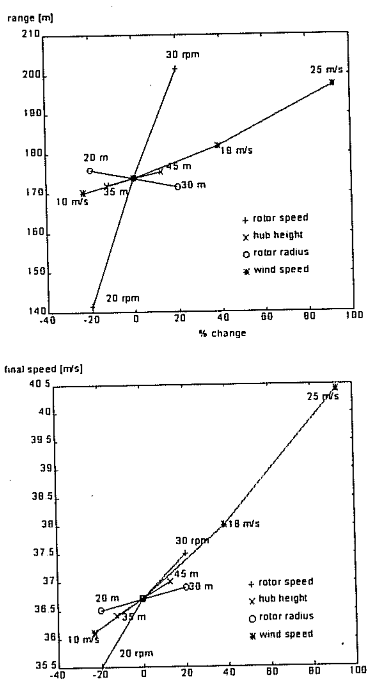

Figure 3: Sensitivity of range and final speed to turbine parameters and wind speed

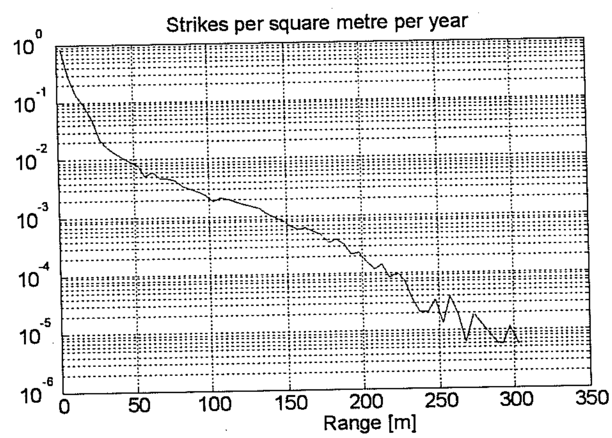

Figure 4: Number of ice fragments per year per square metre of ground area, assuming uniform distribution of wind directions

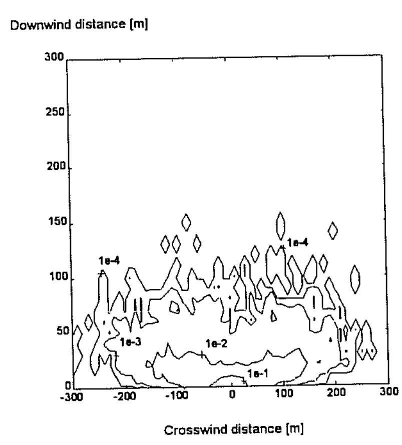

Figure 5: Plan view showing contours of ice fragment strikes per year per square metre of ground area, for a fixed wind direction.