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October 26, 2011

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Subject: Superior Farms Wind Turbine Blade Throw Analysis
Project No. 1107927

Dear Mr. Pimentel:

At your request Exponent has estimated the risks associated with the loss of a blade from a proposed wind turbine at Superior Farms in Dixon, CA. The proposed wind project will utilize one Mitsubishi MWT-1000A (MWT62/1.0) wind turbine. For the purpose of this analysis we have assumed that the wind turbine will be located as shown in Figure 1. Also shown in Figure 1 is a kennel structure that was used for the risk analysis calculations.

Figure 1. Location of wind turbine and kennel structure used for this analysis

The Mitsubishi MWT-1000A wind turbine has hub height of 55 m, blade length of 29.5 m, and rotor diameter of 61.4 m. The turbine has a rotational speed of 19.8 rpm and controls its power and rotational speed using pitch regulation. This report analyzes the risks due to loss of a full blade at nominal operating speed and the loss of a full blade during an overspeed condition.

The probability of an impact occurring due to the loss of a blade is conditional on the prior probability of the wind turbine losing a blade. These prior probabilities have been estimated by the Energy Research Centre of the Netherlands (ECN)[1] as follows:

- Probability of loss of entire blade at nominal operating rpm
  = $4.2 * 10^{-4}$ (1 in 2,400) per year
- Probability of loss of entire blade during mechanical braking (~1.25 times nominal rpm)
  = $4.2 * 10^{-4}$ (1 in 2,400) per year
- Probability of loss of entire blade during overspeed
  = $5.0 * 10^{-6}$ (1 in 200,000) per year

It is our understanding that Mitsubishi has reported to Foundation Windpower that in the entire installed base of MWT-1000A wind turbines, no units have ever entered an overspeed condition. Foundation Windpower has requested additional documentation from Mitsubishi on this subject including the size of the installed base. If requested, Exponent will analyze this data which may further refine the prior probabilities of failure.

Loss of Full Blade at Nominal Operating Speed

Exponent performed a ballistic analysis to determine both the maximum range of a blade following blade failure, as well as the likelihood of the blade striking a specific area within this range. For the purpose of this analysis, we assumed that the center of mass of the blade is located one third the distance from the hub edge to the blade tip, due to the blade's taper. The analysis assumes simple projectile motion, and assumes no aerodynamic forces such as drag.

The ballistic analysis was first performed assuming the loss of an entire blade while operating at the nominal rotational speed of 19.8 rpm. The distance traveled by the blade was calculated for all possible release angles, both 'overhand' and 'underhand.' Under these conditions, the furthest that the center of mass of the blade can travel is 94 m, which can occur if the release occurs at an overhand blade angle of 66 degrees or an underhand blade angle of -55 degrees measured from the horizontal. Assuming that the blade is equally likely to release at any point in its rotation, the probability of the blade traveling further than a given distance is plotted in Figure 2. Note that the tip could be oriented such that it is further away from the tower than the

[1] H. Braam and G.J. van Mulekom, *Analysis of Risk-Involved Incidents of Wind Turbines.* Translated by J. M. Hopemans and C.P. Van Dam and included as Attachment 1 in *Permitting Setback Requirements for Turbines in California* Prepared for the California Energy Commission (CEC) by the California Wind Energy Collaborative (CWEC), November 2006, CEC-500-2005-184.

center of mass, so the damage from the loss of an entire blade could occur at a maximum distance of 114 m from the wind turbine.[2]

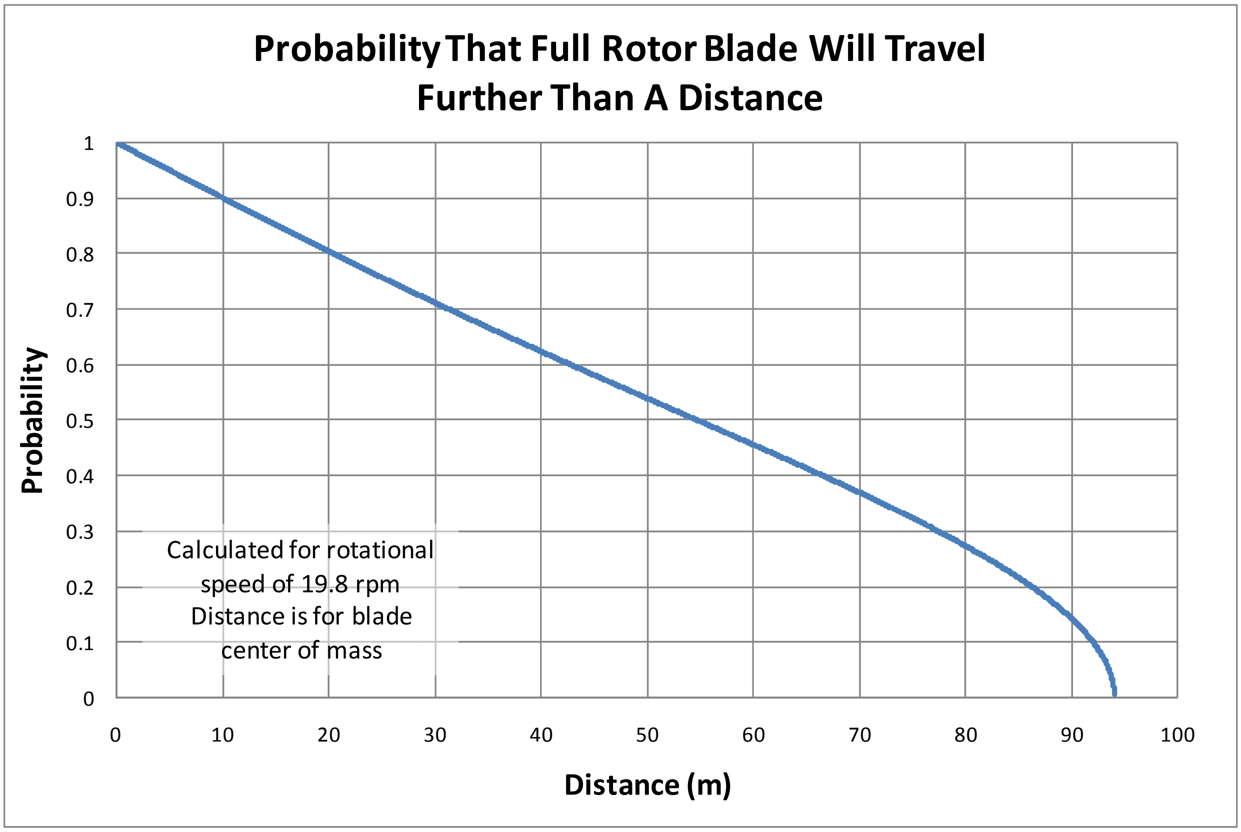

Figure 2. Probability that the center of mass of the blade will travel more than a certain distance following the loss of a full blade at 19.8 RPM. For example, this plot shows that if the full blade is lost, the likelihood of the blade center of mass traveling greater than 90 meters is approximately 0.15.

Loss of Full Blade Above Nominal Operating Speed

The Mitsubishi MWT-1000A has aerodynamic, mechanical, and yaw control braking systems. In the unlikely event that all three of these systems simultaneously fail during high winds, the nominal operating speed could be exceeded. At higher rotational speeds, a blade can travel further and may exceed the distance limits calculated for the nominal operating speed. We have therefore analyzed risks associated with full blade loss occurring during overspeed conditions.

[2] 94 m plus two thirds the length of the blade.

A ballistic analysis was performed at 24.75 rpm, or 1.25 times the nominal rotational speed. This is above the safety system shut down speed for the Mitsubishi MWT-1000A and is characterized in the ECN risk analysis as the speed during mechanical braking. At this speed, the maximum distance the center of mass of the entire blade can travel is 127 m, and therefore with the worst-case blade orientation, the tip of the blade could reach a distance of 147 m from the wind turbine. For comparison, the nearest point on the kennel structure is located approximately 315 m from the wind turbine and the nearest portion of the property on which the kennel is located is approximately 180 m from the wind turbine.

Overspeed conditions can encompass a range of elevated rotational speeds. We performed a ballistic analysis for a rotational speed of 47 rpm, which is the speed that maximizes the likelihood that the kennel structure will be hit by a full blade. The kennel structure is located a distance of 315 to 350 m from the proposed turbine and covers an area of approximately 430 m^2. In our analysis, we expanded this area to 1,800 m^2 to include all locations that a blade could land and be likely to come in contact with a portion of the kennel structure. Assuming the worst case rotational speed of 47 rpm, the likelihood of a lost blade landing in the 1,800 m^2 area near the kennel structure is approximately $4.2 * 10^{-3}$ (1 in 240). As noted earlier in this report, ECN estimates the probability of blade loss occurring during overspeed conditions is $5.0 * 10^{-6}$ (1 in 200,000) per year. Using this estimate, the probability of a blade striking the kennel structure due to blade loss during an overspeed condition is $2.1 * 10^{-8}$ (1 in 48 million) per year. This likely overstates the actual probability as it assumes the overspeed failure always occurs at the worst case turbine speed of 47 rpm. For comparison purposes, in the U.S. the probability of being killed by lightning is 1 in 6.5 million per year, and the probability of being killed due to being bit or struck by a dog is 1 in 9.4 million per year.[3]

The analysis above assumes that the wind turbine is equally likely to be oriented in any direction. In order for the wind turbine to be oriented such that a lost blade would strike the kennel structure, the wind direction would need to be directed from either approximately 53 degrees northeast or 233 degrees southwest. Based on wind data from the California Irrigation Management Information System (CIMIS) sensor in Dixon, wind from both of these directions is less likely than what would be expected by assuming a uniform distribution over wind direction. Furthermore, when wind did blow from these directions, the average wind velocity was lower than the site's historical average wind velocity for all directions. Therefore, the above analysis is likely to overestimate the true probability of a lost blade striking the kennel structure.

Exponent also performed a ballistic analysis to determine the likelihood of a blade lost due to overspeed conditions striking a hypothetical structure located on the kennel property at the corner closest to the wind turbine. For the purpose of this analysis, we assumed a 430 m^2 structure located 180 to 215 m from the proposed turbine and expanded this area to 1,800 m^2 to

[3] National Safety Council, *Injury Facts, 2011 Edition.* Itasca, IL.

include all locations that a blade could land and be likely to come in contact with a portion of the hypothetical structure. The rotational speed that maximizes the likelihood of a blade striking this location is 35 rpm. At this speed, the likelihood of a lost blade striking the hypothetical kennel structure is approximately $1.0 * 10^{-2}$ (1 in 100). Therefore, the probability of a blade striking the hypothetical kennel structure due to blade loss during an overspeed condition is $4.8 * 10^{-8}$ (1 in 21 million) per year. As with the prior calculation, this likely overstates the true probability as it assumes the failure always occurs at 35 rpm, which is the worst case rotational speed for this distance.

Blade Tip Design

The Mitsubishi MWT-1000A wind turbine controls its power and rotational speed using pitch regulation. Therefore, unlike most stall regulated wind turbines, the Mitsubishi MWT-1000A does not have adjustable rotor blade brake tips. Instead, the blade is single piece, and there is no separate blade tip to lose. The ECN report states "Blade fracture is relevant to all turbines; a flyaway tip is only relevant to stall regulated turbines with blade tips," and the data provided in the ECN report does not document a single instance of tip failure in a pitch regulated wind turbine.

Conclusion

- When operating at the nominal speed, should the turbine lose a blade, the blade is unlikely to travel further than 114 meters.
- When operating at 1.25 times the nominal speed, should the turbine lose a blade, the blade is unlikely to travel further than 147 meters.
- The probability of a blade striking the current kennel structure due to blade loss during an overspeed condition is $2.1 * 10^{-8}$ (1 in 48 million) per year.
- The probability of a blade striking a hypothetical kennel structure located at the corner of the kennel property nearest to the wind turbine due to blade loss during an overspeed condition is $4.8 * 10^{-8}$ (1 in 21 million) per year.
- Unlike stall regulated wind turbines, Mitsubishi MWT-1000A does not have separate, adjustable rotor blade brake tips and is therefore not subject to the same risk of loss of blade tip. The ECN review of European wind turbine databases did not report any instances of thrown tips amongst pitch regulated wind turbines.

The analysis reported herein was performed at the request of Foundation Windpower as part of its risk assessment for the proposed installation at Superior Farms located in Dixon, CA, and as such, its scope may not be adequate for other purposes. Use of this report or the findings, conclusions, or recommendations presented herein for any other purpose is at the sole risk of the user. The opinions and findings presented in this report have been formulated within a reasonable degree of engineering certainty. Exponent reserves the right to supplement this report and to expand or modify opinions based on a review of additional material as it becomes available through ongoing discovery or investigation.

Sincerely,

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