Den Brook Wind Farm
Risk Assessment

Prepared for RES UK & Ireland Ltd

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Executive Summary

RES UK & Ireland Ltd are developing a wind farm at Den Brook in Devon. The site will have nine wind turbines; each rated for 2.0 MW electricity generation. The site is in a relatively remote location with no nearby footpaths or roads. However, there is a railway line running through the site, and although this is currently seldom used, it has been proposed that it will be reopened to run nine return services daily.

MMI have carried out a risk assessment for the site to determine risks to the operation of the railway line posed by the wind turbines. A number of wind turbine failure events have been considered which would lead to blade or blade fragments being thrown or dropped from the turbines as a result of operational failures or fires. Risks from thrown and dropped ice have also been included. The cumulative frequency of failure of wind turbine leading to a throw or dropped blade or fragment has been set to 10^{-3} per year (one in 1,000 years) based on previous research carried out by MMI for the Health and Safety Executive.[1]. The frequency of icing has been set to 2.6 per year, based on data from the Met Office.

MMI's in-house software for wind turbine risk assessments (MMI-RAPTur) was developed in conjunction with the research for the HSE and was verified during that work. It has been used to calculate the probabilities of debris and ice landing at particular locations. These have been converted to Location Specific Individual Risks (LSIR) by the application of turbine failure and icing frequencies; the LSIR values have been converted to values of Individual Risk by applying occupancy frequencies. Risks from the wind turbines have been compared with "natural environment risks" from trees and tolerable limits commonly used by the HSE.

In addition to the blade, fragment and ice throw risk assessment a separate tower collapse risk assessment has also been carried out. This is based on a structural assessment of the tower and base slab design to determine the extreme wind loading condition which may cause the tower to collapse. This wind condition can be related to a wind return-period or frequency and hence the tower collapse risk can be assessed alongside the blade, fragment and ice throw risks.

The general findings are:

- The risk to trains passing the site for being hit by wind turbine debris or ice has been calculated to be around one in 64,000 years. If thrown ice is not considered a threat to the trains then the risk reduces to around one in 100 million years, which is negligible.
- The risk to the track for being hit by wind turbine debris from the two nearest turbines (T6 and T8) is around 1 in 50,000 years) which is reasonably low. It should be noted that this is only the risk of debris lying on the track - not the risk of fatality, nor of the train becoming derailed, nor indeed the train running over the turbine debris on the track, all of which will be lower. If visible debris is lying on the track, the train driver may have the opportunity to stop before hitting it – therefore the probability of debris lying on the track and a train hitting it is lower than the probability alone of debris lying on the track. Also, not all derailments cause a fatality so the combined probabilities of (*turbine debris on track x train hit x derailment x fatality*) will be lower than the probability of debris on the line alone.
- By comparison, it is estimated that the risk of trees or tree branches being on the line as a result of high winds is around or 1 in 730 years).

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1.0 INTRODUCTION

RES UK & Ireland Ltd (RES) are developing a wind turbine site at Den Brook in Devon. The site will have nine wind turbines, although the actual wind turbine make and model to be installed has not yet been determined. Each turbine will provide 2 MW capacity, with tower height 75 m and rotor diameter 90 m to give a tip height of 120 m.

The site is in a rural location with no nearby footpaths or roads; however, there is a privately owned railway line running through the site. Two of the wind turbine locations, T6 and T8, are particularly close to the railway line at around 90 m from the base of the towers (Figure 1).The railway line is currently seldom used but the there is a proposal to re-open it with nine return commuter services running daily (information from Dartmoor Railways [10]), to commence in summer 2012. At the time of carrying out this work, there was no information available of train times, running schedules, sizes of trains and speeds.

MMI Engineering Ltd (MMI) has undertaken a risk assessment of the site on request of RES with particular emphasis on the risk to the railway. The particular risks considered are from: blade failure, throw and fragmentation, fire (resulting in catastrophic damage) and ice throw. Additionally a tower collapse risk assessment has been included as a separate part of the same analysis.

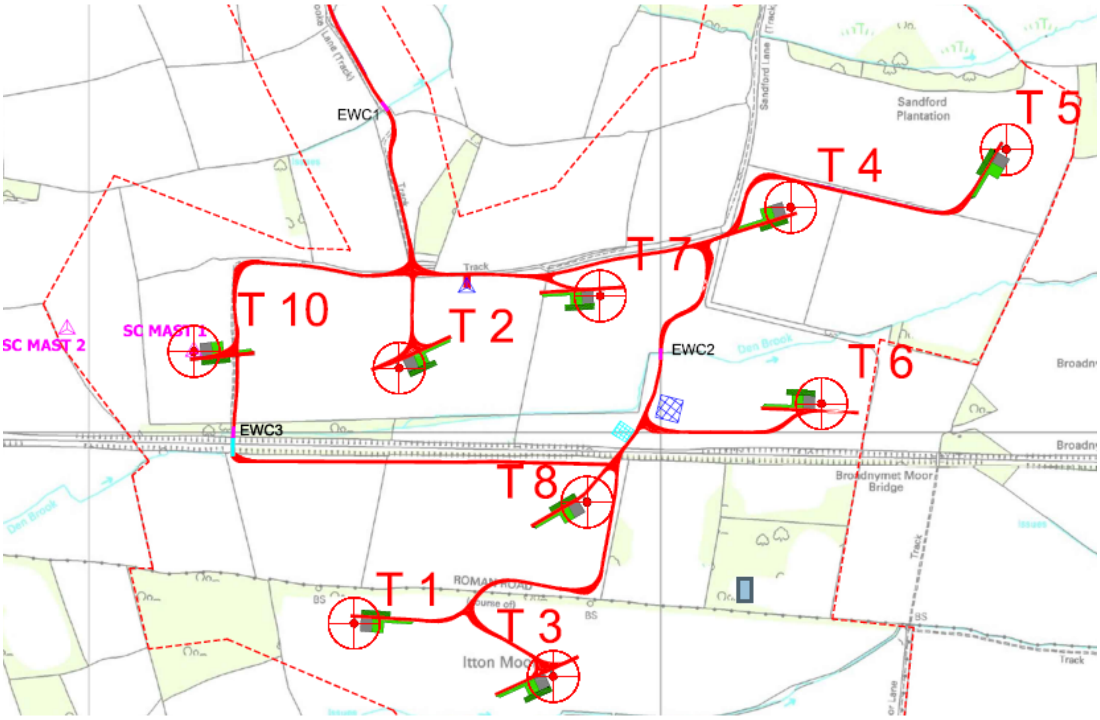

Figure 1- Den Brook site showing the position of the wind turbines and railway line.

2.0 METHODOLOGY

MMI has carried out risk assessment for a single wind turbine at the Den Brook site. As the wind profile at hub height (75 m AGL) will be near uniform, the results of the risk assessment can be applied to any turbine on the site. The actual wind turbine make and model to be installed at the site had not been selected at the time this work was carried out; for the purpose of the risk assessment a Vestas Mk 7 (which is understood to be a candidate wind turbine) was used to define input parameters.

2.1 Analysis Tools

The primary tool used in the analysis is the in-house developed software MMI-RAPTur (Risk Analysis Package for Wind Turbine Failure) which was developed in conjunction with the HSE [1] and recently presented at the Renewables UK Health and Safety 2012 conference [2].

The software uses Newtonian mechanics and a Monte Carlo method to determine the probability of thrown blades, blade fragments and ice landing at any particular location about the base of the wind turbine tower. A number of the variables affecting the blade, blade fragment, and ice flight can be randomly assigned within MMI-RAPTur; this includes objects that are "thrown" when the rotor is initially turning and dropped, when the rotor is stationary. Typically 10^5 sets of variables or "instances" are defined to allow statistical analysis to be carried out on the thrown and dropped objects and contour maps of probability of impact and fatality around the base of the wind turbine to be generated.

More instances can provide more uniform results, but this has an impact on computation time. The number of 10^5 instances has been chosen for the current assessment as it provides reasonably smooth results and requires around a day's computation time per case.

2.2 Analysis Parameters

When the work was started, RES had not made a final decision on which make and model of wind turbine would be used at Den Brook. For the purpose of the risk assessment, RES instructed MMI to use technical data from the Vestas Mk7 wind turbine which is a candidate for the site and is assumed to be representative of all similar wind turbines considered for the site.

The main properties of the turbine and wind conditions pertinent to the risk assessment are summarised in Table 1.

The Monte Carlo method used initially generates uniformly distributed random numbers between 0 and 1 for each variable in the problem. These must then be transformed to random variables having a specific (non-uniform) probability distributions function to match the characteristics of each variable. The different distributions which have been used in the risk assessment methodology are: Uniform, Beta, Weibull, Rayleigh, and Normal distributions. Within the MMI-RAPTur, different distributions can be assigned to different random parameters. The distributions considered for various analysis parameters are listed in Table 2.

Description of Turbine	
Type	Vestas Mk7
Capacity	2 MW
Hub Height	75 m
Blade length	44 m
Rotor Diameter	90 m
Wind & Rotor Speeds	
Cut-in wind speed	4 m/s
Rated wind speed	14 m/s
Cut-out wind speed	25 m/s
Nominal revolution	14.9 rpm
Optimal interval	9.6 - 17 rpm
Runaway speed (2 x Nominal speed)	29.8 m/s

Table 1- General properties of the wind turbine used in the assessment.

Variables	*Value*	*Data Distribution*
Blade / fragment coefficient of drag	1	Constant
Blade / fragment exposed area	Depends on fragment size	Uniform
Blade / fragment mass	Depends on fragment size	Uniform
Blade / fragment angle of detachment	0 to 360^o	Uniform
Rotor speed at incident (rpm)	14.9 (nominal) or 29.8 (runaway)	Constant
Wind speed	Direction dependent	Rayleigh
Air density	1.225 kg/m^3	Constant

Table 2- Data distribution assumed for various parameters

Site specific wind rose data for the Den Brook site was provided by RES. The data provided was for 12 sectors for each of which frequency of occurrence and wind speeds were given. This was transposed to a wind rose with 8 compass points for compatibility with MMI-RAPTur.

The Rayleigh distribution is commonly used to model the distribution of wind speed and was adopted here. This is a special case of the Weibull distribution with "shape factor" equal to 2 and the "scale factor" set to the wind speed.

As the original wind data was obtained from the anemometer at 50 m height. This data was extrapolated to determine the wind speeds at the hub height of 75 m using a log profile for the wind above ground level and a roughness factor of 0.5 which is a conservative estimate for fairly level land with many trees and hedges [3]. The wind data used in the assessment is summarised in Table 3.

Direction	*Frequency of Occurrence*	*Wind Speed (m/s)*
N	0.0406	4.51
NE	0.0458	4.53
E	0.1313	4.70
SE	0.1089	4.56
S	0.0834	5.58
SW	0.1685	6.94
W	0.2816	6.68
NW	0.1398	6.33

Table 3 - Adjusted wind data for the Den Brook site

2.3 Risk Assessment Methodology

Failure Scenarios

There are a range of scenarios which might lead to blades or fragments being thrown or dropped from the wind turbine. Blades may become detached due to equipment failure, poor construction, maintenance errors or extreme environmental conditions. There is less evidence for spontaneous fragmentation of wind turbine blades. However fragmentation may occur as a result of mechanical failure leading to runaway speeds on the rotor, resulting in excessive deflection on the blades and tower strike. Fires in electrical and mechanical equipment have the potential to damage control systems leading to runaway speeds, and can cause debris to fall from the nacelle in addition to the rotor. Icing presents similar risks in that ice which forms on the blades can be throw, potentially with a slingshot effect (i.e. having components of velocity in both the tangential and radial directions). Similarly ice may be dripped from the rotor blades when stationary or the nacelle.

In the risk assessment, mechanical and electrical failure leading to blade or fragment throw, fire and ice risks may be considered as similar events. All these scenarios are handled within the MMI-RAPTur software; the main difference between them in the risk assessment is their frequency of occurrence.

MMI-RAPTur Outputs

MMI-RAPTur calculates contours centred around the base of the wind turbine for the probability of impact of a blade, fragment or ice.

(The software also includes models for harm to people – or probability of fatality - determined from the energy of impact of blades, etc. However these are not required in the Den Brook risk assessment which focusses on risks to the operation of the railway.)

Definition of Risk

Risk is generally defined as the combination of the probability of an event occurring, and the consequence resulting from the event. The consequence is normally an injury to a person or fatality.

There are a number of ways to describe "risk" – a commonly used metric is "Location Specific Individual Risk" (LSIR) which describes the likelihood of fatality to one person if they remain in a given location for a whole year. Another metric is "Individual Risk", which is a measure of the annual risk of fatality to which a person is exposed. Individual Risk (IR) is a valuable parameter to use, since it is this that HSE use to benchmark risk in their guidance on risk – R2P2 [9]. To convert to IR, the LSIR is multiplied by the portion of time that a person is exposed to that LSIR (i.e. the occupancy rate).

The probabilities (probability of impact or probability of fatality by direct impact) calculated in MMI-RAPTur can be converted to LSIR and Individual Risk as follows:

- LSIR = Probability x Frequency of Wind Turbine Failure
- Individual Risk = LSIR x Occupancy Rate

Assumed Frequency of Failure

The overall frequency of failure plays an important part in determining risk and is set conservatively to 10^{-3} per year [1]. As no specific data is available, this frequency is uniformly split between the three principal failure modes considered:

- Blade throw: This may be due to: (i) overspeed leading to structural failure or (ii) poor maintenance leading to blade throw at nominal rotating speed. Frequency of failure is set to 0.333×10^{-3} per year.
- Fragmentation: This is very unlikely to be spontaneous; more likely to be due to tower strike in overspeed condition. Frequency of failure is set to 0.333×10^{-3} per year
- Fire: blade or fragment throw, or debris dropped from the nacelle as a result of fires due to mechanical / electrical failure. (Lightning strike is not included as its 10^{-8} LSIR is too low to be significant). Frequency of failure is set to 0.333×10^{-3} per year

Icing risks are considered separately as these are due to environmental conditions rather than operating or maintenance concerns. The Met Office provides data online for a number of stations around the UK which includes the number of days when air frost occurs. The closest location to the Den Brook site is Chivenor [11] and from this an icing frequency of 2.6 days per year was determined. It is assumed that if icing occurs on the wind turbine then shedding ice by either "drop" (when the rotor is stationary) or "throw" (when the rotor is turning will also occur.

Analysis Grids

Probabilities of a blade, fragment or ice landing at a particular location is calculated on a 5 x 5 metre grid.

2.4 Analysis Cases

Seventeen separate cases were defined for analysis with the following definitions and assumptions:

Blade Throw

It is assumed that blade throw may occur in "normal" operation (nominal rotation speed) and if runaway (overspeed) occurs. (*2 cases*)

Blade Fragmentation

It is assumed that this is most likely to occur as a result of rotor runaway and tower strike and hence only the runaway speed is considered. There are separate cases for fragments which are 0.5x blade length; 0.25x blade length; and 0.00075x blade length. The smallest fragment size is necessary to include the effects of objects with mass around 5 kg which may induce penetrating rather than blunt trauma. (*3 cases*)

Fire

This is split into cases for thrown and dropped objects. For thrown objects it is assumed that the rotor remains rotating at its nominal speed; for dropped objects it is assumed that the rotor is stationary. Four cases are considered for each of these, to determine the effect of full blade and three different fragment sizes. (*8 cases*)

Ice

As for fire, this is split into cases for thrown and dropped ice. Ice throw is considered with and without a slingshot effect; ice drop is considered from different positions on the blade. The mass of the ice is assumed to vary between approximately 0.03 - 300kg. The variation in masses and shapes of the ice fragments is taken into account using Monte-Carlo method. (*4 cases*)

A full description of the cases is provided in Table 4 and Table 5.

2.5 Tower Collapse Analysis

The risks due to tower collapse are not determined by blade, fragment or ice throw and are not included in the MMI-RAPTur analysis software. Instead the tower collapse analysis has been determined from a separate structural assessment which reviews the construction details of the tower and base slab and extracts utilisation and factor of safety information for various designs and stability checks from a similar site. [12].

From this each credible failure mode is reviewed and equivalent factors of safety have been defined for the assumed installation at Den Brook. This is itself used to determine the increase in wind loading required to cause collapse; the frequency of appropriate winds at this strength and hence the risk to the railway from tower collapse.

Description	Rotor Speed		Fragment Details				Frequency
		[rpm]	Length (wrt. to blade)	Length [m]	Mass [kg]	Exposed Area	
Blade Throw	Nominal Speed	14.9	1	44	6000 - 6750	204.16	1.67E-04
	Overspeed	29.8	1	44	6000 - 6750	204.16	1.67E-04
Blade Fragmentation	Overspeed	29.8	0.5	22	3206 - 3544	73.04	1.11E-04
	Overspeed	29.8	0.25	11	1600 - 1772	29.26	1.11E-04
	Overspeed	29.8	0.00075	0.033	4.75 - 5.25	0.06606534	1.11E-04
Fire (throw)	Nominal Speed	14.9	1	44	6000 - 6750	204.16	4.17E-05
	Nominal Speed	14.9	0.5	22	3206 - 3544	73.04	4.17E-05
	Nominal Speed	14.9	0.25	11	1600 - 1772	29.26	4.17E-05
	Nominal Speed	14.9	0.00075	0.033	4.75 - 5.25	0.06606534	4.17E-05
Fire (drop)	Stationary	0	1	44	6000 - 6750	204.16	4.17E-05
	Stationary	0	0.5	22	3206 - 3544	73.04	4.17E-05
	Stationary	0	0.25	11	1600 - 1772	29.26	4.17E-05
	Stationary	0	0.00075	0.033	4.75 - 5.25	0.06606534	4.17E-05

Table 4 - Summary of the blade / fragment case parameters

Description	Rotor Speed		Ice Detail					Frequency
		[rpm]	Thickness [m]	Area [m^2]	Mass [kg]	CG on the blade [m]	Sling Shot	
Ice Throw	Nominal Speed	14.9	0.01 - 0.1	0.035 - 3.5	0.0336 - 336	44	Yes	6.5
	Nominal Speed	14.9	0.01 - 0.1	0.035 - 3.5	0.0336 - 336	44	No	6.5
Ice Drop	Stationary	0	0.01 - 0.1	0.035 - 3.5	0.0336 - 336	25.5	No	6.5
	Stationary	0	0.01 - 0.1	0.035 - 3.5	0.0336 - 336	44	No	6.5

Table 5 - Summary of the icing case parameters

3.0 RESULTS

3.1 Risks Due to Blades, Fragments and Ice

The results which have been calculated using MMI-RAPTur for a single turbine at the Den Brook site are presented in Table 6. These are the Location Specific Individual Risks (LSIR) which provide the probability of being hit by an object and the probability of fatality by direct impact from that object.

(Note that "probability of being hit" cannot properly be termed a "risk", as the formal definition of risk requires there to be a consequence of the event. "Being hit" on its own is not a consequence; whereas "fatality" as a result of being hit with sufficient energy is a consequence. However, the term "LSIR" has been used in the current report for convenience.)

The maximum risks occurring at a number of locations from the tower base are provided. The distances are expressed in multiples of *H,* the tip height (120 m). Of particular relevance is 0.75 *H* which is the typical distance of turbines T6 and T8 from the railway.

The ice cases have a much higher frequency of occurrence than the blade and fragment throw cases; 2.6 days per year compared with $1x10^{-3}$ per year. This results in the ice cases having much higher risks and so the results are presented first without the ice cases and then with the ice cases included.

Distance from Tower Base		***LSIR - Probability of Impact***	
Normalised	***Absolute***	***Ice Omitted from Analysis***	***Ice Included in Analysis***
0.5 *H*	60 m	6.63×10^{-7} per year	1.03×10^{-3} per year
0.75 *H*	90 m	4.21×10^{-7} per year	7.00×10^{-4} per year
1.0 *H*	120 m	2.53×10^{-7} per year	4.40×10^{-4} per year
2.0 *H*	240 m	4.83×10^{-8} per year	5.94×10^{-5} per year
Maximum Value (close to tower base)	0 m	1.09×10^{-5} per year	4.98×10^{-2} per year

Table 6 - Risks due to blade, fragment and ice throw

The risks due to blade and fragment throw (no ice) show the expected trends that LSIR is higher close in to the turbine as blades and fragments which land at a short distance are not spread over as long a circumference as blades, etc thrown over a long distance..

The maximum LSIR values occur close to the tower base are also around two orders of magnitude higher because these include the effects of blade and fragment drop when the rotor is stationary.

The risks results with ice throw/drop events included are significantly higher by around three orders of magnitude, as the frequency of ice throw/drop is around three orders of magnitude higher than the frequency of failure leading to blade/fragmentation throw. However, the same trends are seen – i.e. that risk reduces with distance away from the turbine base.

It is relevant to note that mitigation can be taken against ice risks by observation (to avoid approaching the turbines when ice is present) and condition monitoring (preventing the rotors from turning when ice is present)

3.2 Risks from Tower Collapse

The full calculation for the tower collapse risk assessment is provided in Appendix A. Structural failure leading to tower collapse will only occur in extreme wind conditions estimated to occur with a return period of about 4000 years or a frequency of 2.5 $\times 10^{-4}$ per year.

As the hub height is 75 m and the railway line is typically 90 m away from the base of the closest two turbines (T6 and T8) only the rotors, not the tower can hit the railway line and only if the turbine falls within a particular arc with half angle 41° (see Appendix A for calculation). Hence the probability of the rotors hitting the railway line following a tower collapse will be (41° x 2) / 360° = 0.23. (It will in fact be slightly smaller than this as the calculation assumes one rotor blade is pointing vertically upwards).

The Location Specific Individual Risk for a rotor to hit the railway line (noting that this is not a true "risk" as there is no consequence defined) is:

LSIR = 2.5 $\times 10^{-4}$ x 0.23 = 5.75 $\times 10^{-5}$ per year which is equivalent to 1 event in around 17,000 years

This is also the Individual Risk as the railway track is always present (its occupancy rate = 1.0).

3.3 Risk to Operation of the Railway Line

To determine the potential consequences for the operation of the railway line running through the site, two possibilities are considered: (i) blade/fragment or ice fragments may hit the train while it is passing through the site; (ii) blade/fragments may strike the track and obstruct or impair it.

Blade, Fragments or Ice Hitting a Train

Blades or fragments or ice fragments may hit the train while it is passing through the site; to calculate the risk for this scenario, the risk based on probability of impact is multiplied by the occupancy of the train on the site. The following assumptions are made:

- The train is 70 m long – this is based on a First Great Western Class 158 Express Sprinter which has car length 23 m and is typically configured in a 2 or 3 car set.
- The speed of the train is 50 mph
- There are nine return services passing Den Brook per day; assume these run five days per week only.
- The grid size is 5 x 5 m (area over which separate probabilities are calculated in MMI-RAPTur).

The frequency of occupancy in each grid cell is thus 5.02 x 10^{-4} [yr/yr].

The closest wind turbines to the railway track are T6 and T8 each typically at a distance of 90 m (Figure 1). A new probability of impact profile was calculated by overlaying the results from MMI-RAPTur for a single turbine on the T6 and T8 locations and summing the probabilities where they overlapped for the two turbines.

(The influence of other turbines on the risk posed to the track would be lesser due to the larger separation distance; risks from other turbines have not been included in the current assessment.)

From the combined probability contours about T6 and T8 and the route of the railway track past these turbines, the cumulative "LSIR" risk of impact on the track was calculated. This is merely the summation of risks in each of the grid cells which the track passes through. The "LSIR" risk of blades, fragments and ice hitting the track was found to be 3.09×10^{-2} per year.

The risk for a train being hit directly a by blade, fragment or ice is given by this risk of impact on the track times by the occupancy frequency and is equal to 1.55×10^{-5} per year (or one in around 64,000 years). Note that this is similar to the "Individual Risk" (not LSIR) as it includes the frequency of occupancy, but it is not a true "risk" as no consequence is defined.

If ice is taken out of the analysis and only blades and fragments are considered hitting a train, then the "LSIR" value reduces to 1.96×10^{-5} per year and when times by the frequency of occupancy, the "Individual Risk" value is 9.84×10^{-9} per year or around one in 100 million years.

(Ice throw has a significant effect on the analysis as it has a frequency around x1000 more common than blade/fragment throw).

It should be noted that the risks calculated would linearly increase with increase in train length or reduction in speed. However, this is unlikely to change the order of the risks calculated.

Blade or Fragments Hitting the Track

Blades or fragments may strike the track and obstruct or impair it so that it causes disruption to the railway operation. Large pieces of a blade lying over a railway track could potentially derail a fast moving train, resulting in a serious incident. It is reasonable to assume that the track would be affected by the large fragments of the blade only. The chances of ice obstructing or damaging the track or affecting the railway operation are low as ice is likely to shatter on impact with no fragments remaining which would be sufficient to derail a train.

Thus, the LSIR for the probability of impact has been re-calculated for T6 and T8 by combining the cases for the turbine failure leading to blade throw only and not including ice.

The cumulative risk for blade/fragments impacting the track is calculated by summing the risk of impact along the track passing through the site. As the track is present at all times throughout the year the frequency of occupancy is 1.0.

The cumulative risk of impact for the track is 1.96×10^{-5} per year, which is around one in 50,000 years. The risk calculated here is conservative as it is assumed that all fragments of the blade landing on the track would affect the railway operation, which may not be necessarily true. For example, smaller pieces and sections of the laminate blade construction are unlikely to derail a train.

3.4 Comparison with Risks from Trees

To put into context the risks to trains and the railway line, a comparison has been made with the risk from the trees close to the railway. The track on the Den Brook site is surrounded by tall trees (Figure 2) for a distance up to 25m along the track [4]

Figure 2- Railway track surrounded by tall trees on the site.

From the site photos provided by RES, it appears that site has beech and birch trees. The height of a mature beech is around 40 m and it has a lifespan of more than a hundred years; while a mature birch has a height of 30 m and lifespan of rarely greater than 100 years [5, 6]. However, at the end of a tree's life it is unlikely to spontaneously fall without outside influence – such as a strong wind. It is more likely to decay in-situ.

During high winds, branches may break off the trees or trees can be broken or uprooted. According to the Beaufort Scale this may happen in a strong gale at wind speeds of greater than around 20 m/s [7].

As the track is oriented along E-W direction, the trees are to the North and South of the track, and it can be assumed that only the winds from NW to NE and SW to SE would cause trees to fall on the railway line. From the wind rose provided by RES, the frequency of the wind exceeding 20 m/s in these directions is 3.42×10^{-5} per year.

The risk of the wind causing any tree or branch next to the line to fall is then:

(Probability of wind damage) x (frequency of high wind in the correct wind direction) x (number of trees) = 1.37×10^{-3} per year (or around 1 in 730 years).

The general guidance from HSE is that an individual risk of death of one in a million per year for both workers and the public corresponds to a very low level of risk and should be used as a guideline for the boundary between the "broadly acceptable" and "tolerable" regions.

4.0 SUMMARY OF RISKS

4.1 Risks to the Railway Track

A summary of the risks presented to the railway line is provided in Table 7 and Figure 3 – these are both “LSIR” and “IR” as the railway track is always present and the occupancy rate = 0.1.

Item	*Description*	*Risk [per year]*
1.	Tower collapse - risk of rotor on track.	5.75 x10^{-5}
2.	Blade, fragments or ice hitting a train	1.55 x10^{-5}
3.	Blade or fragments hitting a train (no ice)	9.84 x10^{-9}
4.	Blade or fragments hitting the track	1.96 x10^{-5}
5.	Risk of tree or branch on track as a result of high winds	1.37 x10^{-3}

Table 7 - Summary of risks posed to the railway track

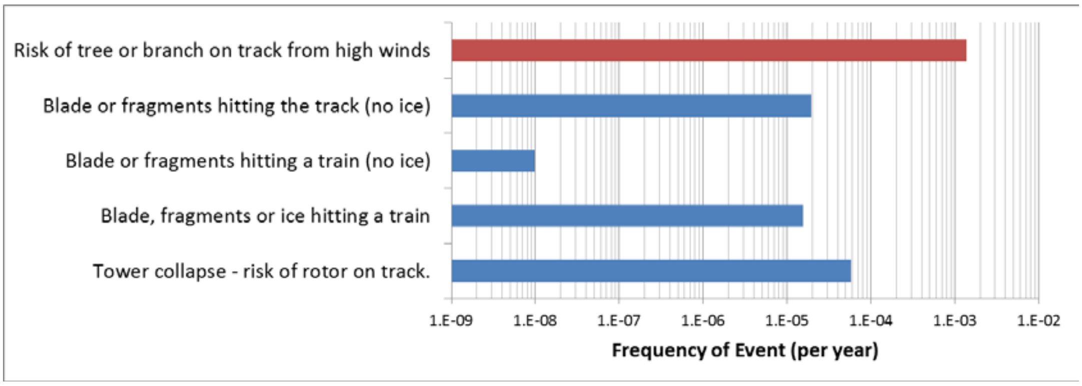

Figure 3 - Summary of risks posed to railway track

The total risk to the track due to the two wind turbines adjacent to it (T6 and T8) is conservatively calculated from the sum of items 1 and 4:

= 7.71 x10^{-5} per year or 1 in around 13,000 years

This can be compared with the risk of trees or branches on the track:

= 1.37 x 10^{-3} per year or 1 in around 770 years.

4.2 HSE Context

To put this into context, HSE uses the concept of “Tolerability of Risk” – i.e. the risks that the public will accept for various activities. This has a degree of subjectivity in it, so for example, some cited tolerable risks are:

- 5.34 $\times 10^{-8}$ per year risk of death by lightning [9] or 1 event per 18.7 million years
- 1 $\times 10^{-6}$ per year general risk of death in an explosion or fire at home [8] or 1 in 100,000 years
- 1 $\times 10^{-4}$ per year for the public who have a risk imposed on them “in the wider interest of society” [9] or 1 in 10,000 years

In the HSE’s *Reducing Risk, Protecting People (R2P2)* document [9], an approach is described with three levels of ascending risk:

1. Broadly acceptable
2. Tolerable – provided that the nature and level of risks are properly assessed and used to develop control measures; and that the residual risks are not unduly higha and are kept as low as reasonably practicable (ALARP).
3. Unacceptable

Note that *R2P2* does not describe these as limits imposed by HSE but rather as general observations on what is considered acceptable and unacceptable by society.

The boundary between “broadly acceptable” and “tolerable” risks is generally taken as 10^{-6} per year individual risk of fatality (1 in a million years). The boundary between “tolerable” and “unacceptable” is generally taken for the public at large as 10^{-4} per year risk of fatality (1 in 10,000 years).

The risks to the railway track posed by (i) tower collapse, and (ii) blade, fragments or ice summarised in Table 7 appear to fall into the “tolerable” region. However it is important to recall that the “risks” shown in Table 7 do not have a consequence associated with them – they are properly the probability of turbine debris lying on the track. To convert them to true risks for comparison with the tolerability limits discussed by HSE, it would be necessary to determine fatality rates from these probabilities.

There are a number of factors which reduce the potential fatality rate as a result of turbine debris on the railway in comparison with the probability of debris on the line. For example, the train driver has the opportunity to spot debris and stop the train before impact. If the train does impact debris, it does not necessarily become derailed; and even if the train does become derailed, this does not necessarily cause fatality to passengers.

It is difficult to ascribe numerical values to these events; however, the individual probabilities for (i) the train hitting the debris (ii) the train becoming derailed if it hits the debris and (iii) fatalities occurring as a result of the derailment, will all be less than one. Hence the combined probabilities of (*turbine debris on track x train hit x derailment x fatality*) will be lower than the probability of debris on the line alone. Once all these mitigating factors are taken into account it is likely that the risk of fatality to rail users falls comfortably within the “tolerable” region and possibly within the “broadly acceptable” region.

5.0 CONCLUSIONS

MMI has carried out risk assessment for the Den Brook site. As the contract for the wind turbines at the site has not yet been placed, the risk assessment input parameters have been based on a Vestas MK 7 turbine (which is one of the candidates for the site) at RES' instruction. The in-house developed software MMI-RAPTur (Risk Analysis Package for Wind Turbine Failure) has been used for the blade, fragment and ice throw and drop analysis. This was used to generate a series of contour plots around the base of the wind turbine for the probability of impact and probability of fatality by direct impact, from thrown blades and blade fragments (operational failure and as a result of fires) and from ice. The calculated probabilities of fatality have been converted to Location Specific Individual Risk (LSIR) and Individual Risk (IR) by application of appropriate turbine failure, icing and occupancy frequencies. A separate structural assessment has been undertaken to determine the wind strength required and hence the frequency of tower collapse.

The principal result is the risk of impact to the track or a train passing through the site, as this will help determine any consequences for the operation of the railway. Two cases have been considered: (i) the train being hit by a blade, blade fragment or ice, and (ii) railway track being impacted by a blade or blade fragment.

- The risk for the train being hit by a blade, blade fragment or ice is of the order of 10^{-5} per year (calculated to be around 1 in 64,000 years. The low risk is attributed in part to the low probability of impact of turbine debris on the track and in part to the low frequency of train presence on the site. If it is considered that ice hitting the train poses no threat, and ice is removed from the analysis, then the risk of a train being hit by blade or fragment only is of the order 10^{-8} per year or around one in 100 million years.
- The risk of a blade or blade fragments impacting the railway track on the site from two nearest turbines (T6 and T8) is of the order 10^{-5} per year (calculated to be around one in 50,000 years). This risk is reasonably low. It should be borne in mind that this is not the risk of fatality, nor of the train becoming derailed, nor indeed the train hitting turbine debris on the track. It is merely the risk of there being turbine debris on the track. If visible debris is lying on the track, the train driver may have the opportunity to stop before hitting it – therefore the probability of debris lying on the track and a train hitting it is lower than the probability alone of debris lying on the track. Also, not all derailments cause a fatality so the combined probabilities of (*turbine debris on track x train hit x derailment x fatality*) will be lower than the probability of debris on the line alone.
- The risk of the rotor lying on the track as a result of tower collapse is around 6 $\times 10^{-5}$ per year (or around one in 17,000 years)

To put these results in context, the "natural environment risk" to the track from fallen trees or branches has been estimated. The risk that trees or branches may fall on the track as a result of high winds is estimated at around 10^{-3} per year (calculated to be around 1 in 730 years).

The "risk" that there may be trees on the track is therefore several orders of magnitude higher than the "risk" of debris from wind turbines, and it appears that the presence of tree debris on the track from natural causes is much more likely than wind turbine debris. Note that these are not true "risks" as no consequence (such as injury or fatality) has been defined for these cases.

6.0 REFERENCES

[1] *Study and Development of a Methodology for the Estimation of the Risk and Harm to Persons in the Vicinity of Wind Turbines.* MMI Engineering report number MMU204-06-R-01, Issue 6, January 2012, for The Health and Safety Executive. This report will be published as a HSE research report in 2013.

[2] *A Risk Assessment Methodology for Onshore Wind Turbines Developed for the UK HSE* C. Robinson, MMI Engineering, RenewableUK Health & Safety Conference, Manchester, February 2012

[3] *An Introduction to Boundary Layer Meteorology* Roland B. Strull, Kluwer Academic Publishers, 1988.

[4] Conversation between Daniel Leahy (RES) and Chris Robinson(MMI) at the kick-off meeting for the project. RES, Kings Langley, May 2012.

[5] *Trees*. Allen J. Coombes. Pub. Dorling Kindersley Handbooks, 2000

[6] *Beech* Royal Forestry Society, 2012 (Online) Available from: http://www.rfs.org.uk/learning/Beech [Accessed 19 July 2012]

[7] *Beaufort Scale* BBC Weather, 2010 (Online) Available from: http://web.archive.org/web/20101015004110/http://www.bbc.co.uk/weather/features/understanding/beaufort_scale.shtml [Accessed 19 July 2012]

[8] *Tolerability of Risk from Nuclear Power Stations*. HSE Books 1992

[9] *Reducing Risk, Protecting People (R2P2)*. HSE Books 2001

[10] Email from Daniel Leahy (RES) to Chris Robinson (MMI) sent 24/09/2012 at 11:52 *Subject : Den Brook*

[11] *Chivenor* Met Office Historic Station Data, 2013, (Online) Available from: http://www.metoffice.gov.uk/climate/uk/stationdata/chivenordata.txt [Accessed 02 January 2013]

[12] RES Report Reference 01906-005588, date July 2010

APPENDIX A – RISK ASSESSMENT FOR TOWER COLLAPSE

A.1. Introduction

This calculation is prepared to support the requirement to carry out an assessment of the likelihood of structural collapse of the Den Brook wind turbines so that the associated risks arising from collapse. The design details for Den Brook are not yet developed so the opinion is based on design details for a reasonably similar design of wind turbine with data supplied to MMI by RES..

A.2. Methodology

The approach to this assessment is as follows:

1. Review and describe the construction details of the tower base region
2. Extract stress utilisation and factor of safety information for various design and stability checks using site data supplied by RES.
3. Consider each credible failure mode and review the margins to failure. Comment on whether the failure mode is ductile or non-ductile and provide an opinion of the likely consequences of failure
4. Estimate the equivalent FOSs for Den Brook, as far as possible
5. Determine the increase in wind loads necessary to cause collapse and relate this to a wind speed recurrence period

A.3. Wind Turbine Description

At the time of writing the wind turbine design to be used at Den Brook has not been selected. However, a candidate wind turbines is the Vestas V90-2.0MW Mk7 device which has a hub height of 75m and a blade length of 45m. The turbines are separated from the adjacent railway line by a minimum of 90m, so in the event of a collapse the blades could reach the railway although the tower could not. The turbines comprise steel towers built off reinforced concrete spread foundations on dense gravel and weak rock.

The tower is built from a tapered steel cylinder which is fixed at the base. The tower has a diameter of approximately 3 m at the base. The wall thickness of the mast is not known but is in the order of 40 mm thick. It is understood that the bottom section of the tower is likely to be attached directly to cast-in holding down bolts. There are understood to be a large number of HD bolts (say 80 No at 100-150 mm centres) provided to transfer the base moments and shear forces.

The anchor bolts will be secured into the RC base with an assumed ring-type anchor plate. The octagonal RC base is estimated to have a "diameter" of about 15 metres, based on preliminary geotechnical suggestions. The safe bearing capacity is about 500kPa (which includes a Factor Of Safety, FOS = 3). The foundation has a flat bottom, which is founded approximately 2.5 m below ground level. The top surface of the foundation slopes away from the tower with a minimum thickness of about 800 mm at the outer edge.

The RC footing has a structural bottom mat of reinforcement, typically comprising H32 bars at 100mm centres in both directions. The sloping top surface is provided with radial H32 and H20 bars with H20 circumferential distribution bars. The inner two-thirds of the foundation is provided with vertical shear reinforcement. This shear reinforcement comprises H12 bars at spacings of approximately 250-300 mm in each direction.

Concrete has a grade C30/37 and all reinforcement is Grade 500 high tensile reinforcement.

A.4. Review of Failure Modes

Reference is made to design information for an existing wind turbine site to understand the range of failure modes considered in design and the typical FOS associated with each.

<u>Foundation Stability</u>

1. **Overturning** - depending on soil type the FOS on normal extreme wind loading is 1.9 - 2.2. For abnormal extreme wind loading these reduce to 1.8 - 2.0.
2. **Bearing pressure** - for normal extreme loading the bearing pressures are as high as 188 – 225 kPa, compared to an allowable range of 316 – 368 kPa i.e. the FOS = 1.6 - 1.7
3. **Sliding** - large FOS of 9 - 12 is reported so this is not a critical failure mode
4. **Foundation stiffness** - The minimum foundation stiffness range is 62 - 67 GNm/rad compared to an allowable minimum of 50 GNm/rad. The FOS on this parameter is 1.2-1.3 and it was noted that the soil is not susceptible to degradation under cyclic loading i.e. adverse softening should not occur over time.
5. **Settlement** - maximum absolute settlements are calculated to be 24 mm, compared to an acceptable value of 100 mm. Differential settlement is estimated as 0.11° compared to 0.15° allowable, indicating a FOS = 1.36.

If cyclic degradation is discounted on the basis of it being possible to measure and monitor and differential settlement discounted as a serviceability rather than stability concern, stability appears to be governed by bearing capacities. Exceedance of bearing capacity will initially tend to result in larger displacements as the ultimate soil capacity is approached. Wind loads could increase by 1.6 - 1.7 times before stability would be compromised but the consequences would be limited to permanent tilting and loss of functionality.

Deformation of the ground in itself is unlikely to cause collapse.

Once ultimate bearing pressures are reached gross failure of the ground and topple of the turbine could occur, as shown in the sketch below left (Figure 5). However due to the relatively large FOS inherent in allowable bearing capacities i.e. 1.6 - 1.7 times 2.5 - 3.0 = 4 - 5 overall, this should be a relatively unlikely scenario.

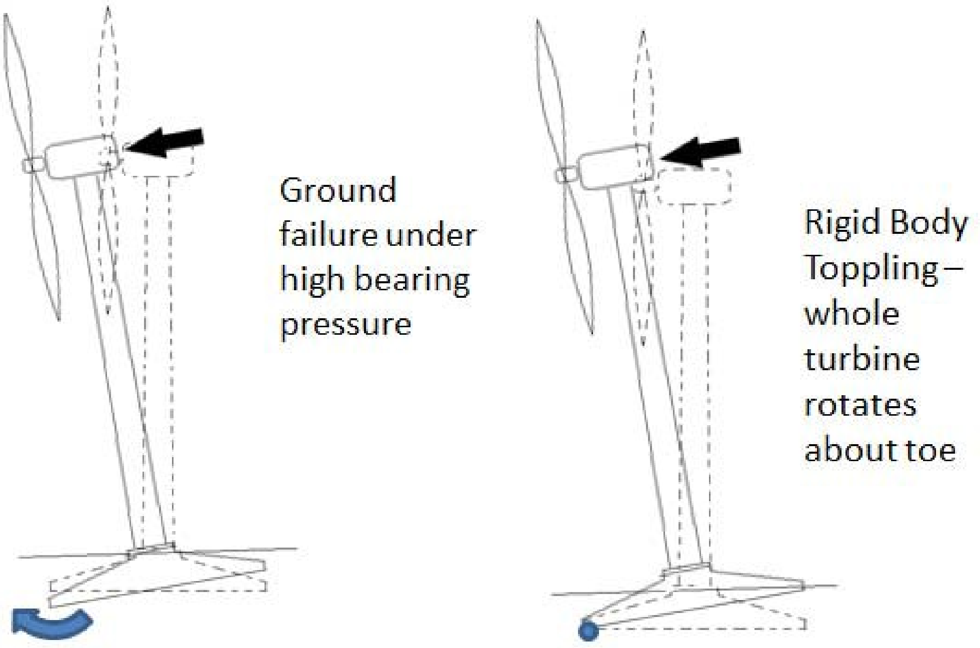

Figure 4. Sketch showing potential toppling scenarios.

If ground failure did not occur, gross rigid body topple, as shown in the sketch below right, would not occur until the COG fell outside the base footprint at which time second-order.

P-delta behaviour would take over i.e. the COG of the tower would need to displace by about 8 m. This would require a huge amount of energy to displace the COG by the necessary horizontal and vertical distances. Therefore it is likely that structural failure of the base slab would occur before such severe rotation took place. Structural failure is discussed below.

Structural Failure of Base Slab

Consideration has been given to the following structural failure modes:

1. **Bending** of octagonal base raft - the maximum utilisation of the bottom mat is 0.95 and for the top mat is 0.89 i.e. FOS = 1.05 - 1.1
2. **Bending** and **shear** of plinth - max utilisation at ULS = 0.52; this is not a critical region.
3. **Shear** of octagonal base raft - the maximum utilisation is 0.94 i.e. FOS = 1.05
4. **Crack widths** are up to 0.29 mm which is on the limit of 0.3 mm.

It is evident that the foundation rafts work quite hard in bending and shear. However, modern code design includes built-in factors of safety and should support ductile detailing. For example the load factor on wind loads is 1.35. While the base might start to experience noticeable cracking when the utilisation exceeds 1.0 significant structural yield is unlikely until the utilisation is about 1.5. Once yield initiates there will be progressive yielding of more of the base slab. Following this elasto-plastic behaviour there may be some plastic deformation although this may not be significant on the Den Brook bases because the shear utilisations are also high (if the base was strong in shear then ductile flexural deformation could be permitted).

If the base slab is loaded sufficiently to fail in a combination of flexure and shear (as shown in the sketch below left, Figure 6) then there will be some plastic deformation but a sudden loss of shear strength seems likely. Once this happens the lateral resistance to wind loading would be greatly reduced and the likely consequence would be gross topple of the mast because the COG would then only need to have been offset by 1 - 2 metres for P-delta to take over.

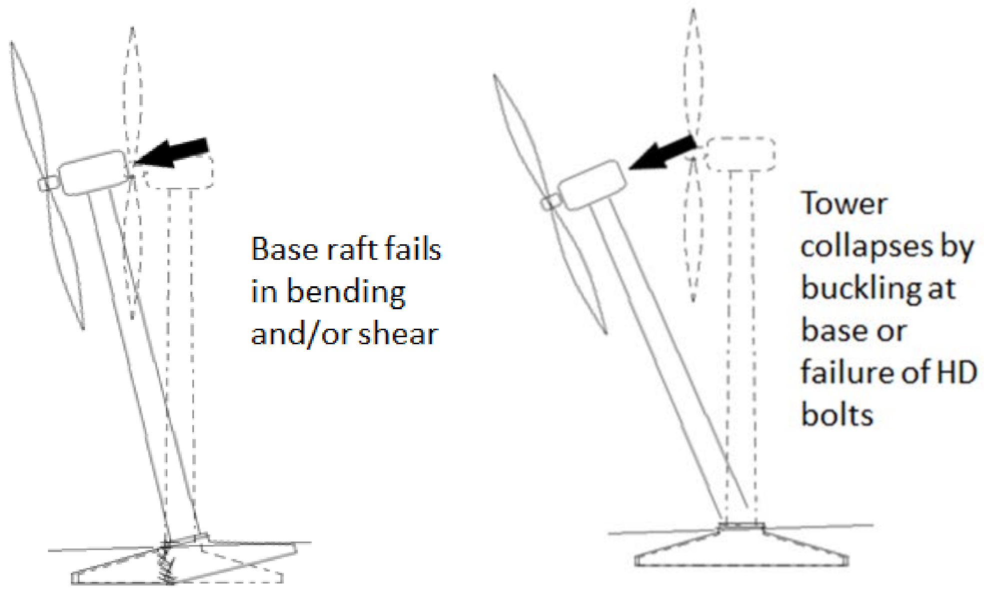

Figure 5. Base slab loading scenarios

A.5. Factors of Safety for Den Brook

Den Brook is not as tall as the reference site (75 m c.f. 105 m) so the wind load demands will be less. For example, the maximum base moment at Den Brook is 49.4 MNm compared with 66.6 MNm at the reference site. It is understood that the foundation will be smaller (say 15 m compared to 18 m). Therefore while demands reduce by 35%, the lever arms also reduce by about 20%. The thickness of the raft at Den Brook is not known. For the purposes of this assessment the design reference site FOSs are used directly.

One change for Den Brook is that rather than the lowest section of the tower being cast into the foundation raft, it will instead be secured using cast-in holding down bolts. This introduces another failure mode which is failure of the HD bolts.

If HD bolts fail this would tend to be a progressive effect i.e. the strength does not rely on a single HD bolt. There is therefore some potential for energy absorption due to progressive failure but if this occurred under sustained wind loads then once one bolt fails the others will progressively fail.

It is assumed that the HD bolts will be made stronger than the lowest section of the tower so that the ultimate strength is not reduced and potential for non-linear behaviour is maximised. The strength of the tower is therefore assumed to be governed by the relatively non-ductile failure mode of tower buckling which could lead to a tower-topple failure mode as shown in the sketch above right (Figure 6).

A.6. Specific Investigation into Tower Buckling Strength

The following calculation is carried out using guidance in the DNV/Riso document "Guidelines for Design of Wind Turbines". Site data provided by RES [12] is used for normal extreme loads.

Axial load on tower $N_d := 3422 \cdot kN$

Moment at base of tower $M_d := 62850 \cdot kN \cdot m$

Normal extreme values as taken from RES Report Ref 01906-005588

Height of tower $H := 105 \cdot m$

Radius of tower $R := \dfrac{3949 \cdot mm}{2} = 1.975\,m$ *Drg 01906-D3005-07*

Shell thickness $t := 40 \cdot mm$ *Scaled from drawings and confirmed by RES as a reasonable shell thickness*

Stress due to axial force $\sigma_{ad} := \dfrac{N_d}{2 \cdot \pi \cdot R \cdot t} = 6.9 \cdot MPa$

Stress due to bending moment $\sigma_{bd} := \dfrac{M_d}{\pi \cdot R^2 \cdot t} = 128.3 \cdot MPa$

Reduction factor $\varepsilon_a := \dfrac{0.83}{\sqrt{1 + 0.01 \cdot \dfrac{R}{t}}} = 0.68$

$$\varepsilon_b := 0.1887 + 0.8113 \cdot \varepsilon_a = 0.74$$

$$\varepsilon := \frac{\varepsilon_a \cdot \sigma_{ad} + \varepsilon_b \cdot \sigma_{bd}}{\sigma_{ad} + \sigma_{bd}} = 0.74$$

Young's modulus $E_d := 205000 \cdot MPa$

Poisson's ratio $\upsilon := 0.3$

Design yield stress $f_{yd} := 275 \cdot MPa$

Elastic compressive stress $\sigma_{el} := \dfrac{E_d}{\dfrac{R}{t} \cdot \sqrt{3 \cdot \left(1 - \upsilon^2\right)}} = 2513 \cdot MPa$

Relative slenderness ratio for local buckling $\lambda_a := \sqrt{\dfrac{f_{yd}}{\varepsilon \cdot \sigma_{el}}} = 0.385$

Critical compressive stress	$\sigma_{cr} := \left(1.5 - 0.913\cdot\sqrt{\lambda_a}\right)\cdot f_{yd} = 257\cdot MPa$
Euler force on a cantilever beam	$N_{el} := \dfrac{0.25\cdot\pi^2\cdot E_d\cdot\pi\cdot R^3\cdot t}{H^2} = 44381\cdot kN$
Relative slenderness for global stability	$\lambda_r := \sqrt{\dfrac{\sigma_{cr}}{\left(\dfrac{N_{el}}{2\cdot\pi\cdot R\cdot t}\right)}} = 1.694$
Core radius of a tube	$k := \dfrac{R}{2}$
Equivalent geometric imperfection	$e := 0.49\cdot\left(\lambda_r - 0.2\right)\cdot k = 0.723\,m$
Additional increment of imperfection	$\Delta e := if\left[e > \dfrac{2\cdot H}{1000}, \left(e - \dfrac{2\cdot H}{1000}\right), 0\right] = 0.513\,m$
Total imperfection	$e_{tot} := e + \Delta e = 1.235\,m$
Check that total stress is less than critical stress	$\sigma_{tot} := \dfrac{N_d}{2\cdot\pi\cdot R\cdot t} + \dfrac{M_d + N_d\cdot e}{\pi\cdot R^2\cdot t} = 140.23\cdot MPa$
	$Report := if\left(\sigma_{tot} < \sigma_{cr}, \text{"OK"}, \text{"Not OK"}\right)$ $\boxed{Report = \text{"OK"}}$
Factor of safety against wall buckling	$\boxed{FOS := \dfrac{\sigma_{cr}}{\sigma_{tot}} = 1.83}$

The above factor of safety was recalculated for different shell thickness to test the sensitivity:

- t = 40 mm, FOS = 1.83
- t = 35 mm, FOS = 1.57
- t = 30 mm, FOS = 1.30
- t = 25 mm, FOS = 1.05

It was also tested for increasing wind load, assuming 40mm shell thickness:

- M_d = 62850 kNm, FOS = 1.83
- M_d = 70000 kNm, FOS = 1.66
- M_d = 80000 kNm, FOS = 1.47
- M_d = 100000 kNm, FOS = 1.19
- M_d = 120000 kNm, FOS = 1.00

Therefore the applied wind moment may increase by a factor of 1.9 before the buckling strength of the tower is exceeded, assuming that the shell thickness is 40 mm.

Due to the non-ductile nature of buckling failure modes this would represent the threshold of failure.

A.7. Wind Loading Relationship

The reference turbine has a design lateral load of about 600kN and this is applied at a load point = 0.96H. (H is the nacelle or hub height in this analysis - not the tip height)

The Den Brook lateral load is 650kN applied at a load point = 1.0H

It is evident that virtually all the wind load comes from the turbine itself i.e. the aerodynamic blade loads. The aerodynamic drag on the nacelle and tower appear to be relatively small.

The wind loading on the turbine blades is a function of the resulting relative inflow wind velocity which is a function of the inflow velocity and the tangential slipstream wind velocity. However, the lift and drag forces are then simply a function of the resulting velocity squared.

The probability factor for wind loads is based on BS 6399-Part 2.

Minimum FOS	$FOS_{min} := 1.05$	shear/flexure of foundation raft
Load factor	$\gamma_f := 1.35$	
Material factor on steel	$\gamma_m := 1.05$	
Minimum margin to failure	$SF := FOS_{min} \cdot \gamma_f \cdot \gamma_m = 1.49$	shear/flexure of foundation raft
Allowable increase in wind speed	$SF_w := \sqrt{SF} = 1.22$	
Annual probability of being exceeded i.e. 1 in 50 year recurrence	$Q_{50} := 0.02$	Design case
Wind speed probability factor	$S_{p50} := \sqrt{\frac{5 - \ln(-\ln(1 - Q_{50}))}{5 - \ln(-\ln(0.98))}} = 1$	OK
Annual probability which gives wind increase factor	$Q_{inc} := 0.00025$	
Increased wind speed probability factor	$S_{pinc} := \sqrt{\frac{5 - \ln(-\ln(1 - Q_{inc}))}{5 - \ln(-\ln(0.98))}} = 1.222$	OK
Wind recurrence period at failure	$R_f := \frac{1}{Q_{inc}} = 4000$	years

Therefore the recurrence period for wind loading which will case the wind turbine to collapse due to failure of the foundation in shear is approximately 4000 years or 2.5 $x10^{-4}$ per year which is similar to, and slightly lower than the assumed total frequency of failure for the blades

A.8. Potential Impact on Railway Line

The wind required to cause the tower to collapse will be an unusual meteorological condition and will not be represented by the normal wind rose. Instead it is assumed that the wind can come from any direction.

The turbine nacelle height is H = 90 m, the tip height H_{tip} = 120 m and distance from the railway, L = 90 m. Only the rotors, not the tower can hit the railway line and only if the turbine falls within a particular arc with half angle = cos (90/120) = 41°. Hence the probability of the rotors hitting the railway line following a tower collapse will be (41° x 2) / 360° = 0.23. (it will in fact be slightly smaller than this as the calculation assumes one rotor blade is pointing vertically upwards).

Hence the Location Specific Individual Risk for a rotor to hit the railway line (noting that this is not a true “risk” as there is no consequence defined) is:

LSIR = 2.5 $x10^{-4}$ x 0.23 = 5.75 $x10^{-5}$ per year (or 1 in 17,300 years)