3.0 EFFECTS OF LOW FREQUENCY SOUND AND INFRASOUND

3.1 Humans

3.1.1 Threshold of hearing

Moeller and Pedersen (2004) present an excellent summary on human perception of sound at frequencies below 200 Hz. The ear is the primary organ for sensing infrasound. Hearing becomes gradually less sensitive for decreasing frequencies. But, humans with a normal hearing organ can perceive infrasound at least down to a few hertz if the sound level is sufficiently high.

The threshold of hearing is standardized for frequencies down to 20 Hz (ISO 226:2003). Based on extensive research and data, Moeller and Pedersen propose normal hearing thresholds for frequencies below 20 Hz (see Figure 3.1-1). Moeller and Pedersen suggest that the curve for normal hearing is "probably correct within a few decibels, at least in most of the frequency range."

The hearing thresholds show considerable variability from individual to individual with a standard deviation among subjects of about 5 dB independent of frequency between 3 Hz and 1000 Hz with a slight increase at 20 – 50 Hz. This implies that the audibility threshold for 97.5% of the population is greater than the values in Figure 3.1-1 minus 10 dB and for 84% of the population is greater than the values in Figure 3.1-1 minus 5 dB. Moeller and Pedersen suggest using the pure-tone thresholds in Figure 3.1-1 for non-sinusoidal sound; this relationship is what is used in ISO 226 (International Organization for Standardization) for frequencies down to 20 Hz.

Below 20 Hz as frequency decreases, if the noise source is tonal, the tonal sensation ceases. Below 20 Hz tones are perceived as discontinuous. Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears.

3.1.2 Loudness

Below 100 Hz, the dynamic range of the auditory system decreases with decreasing frequency, and the compressed dynamic range has an effect on equal loudness contours: a slight change in sound level can change the perceived loudness from barely audible to loud. This combined with the large variation in individual hearing may mean that a low frequency sound that is inaudible to some may be audible to others, and may be relatively loud to some of those for whom it is audible. Loudness for low frequency sounds grows considerably faster above threshold than for sounds at higher frequencies. (Moeller and Pedersen, 2004)

3.1.3 Non-auditory perceptions

Non-auditory perception of low frequency and infrasound occurs only at levels above the auditory threshold. In the frequency range of 4 – 25 Hz and at "*levels 20 - 25 dB above [auditory] threshold it is possible to feel vibrations* in various parts of the body, e.g., the lumbar, buttock, thigh and calf regions. A feeling of pressure may occur in the upper part of the chest and the throat region" [emphasis added]. (Moeller and Pedersen, 2004).

3.2 Residential Structures

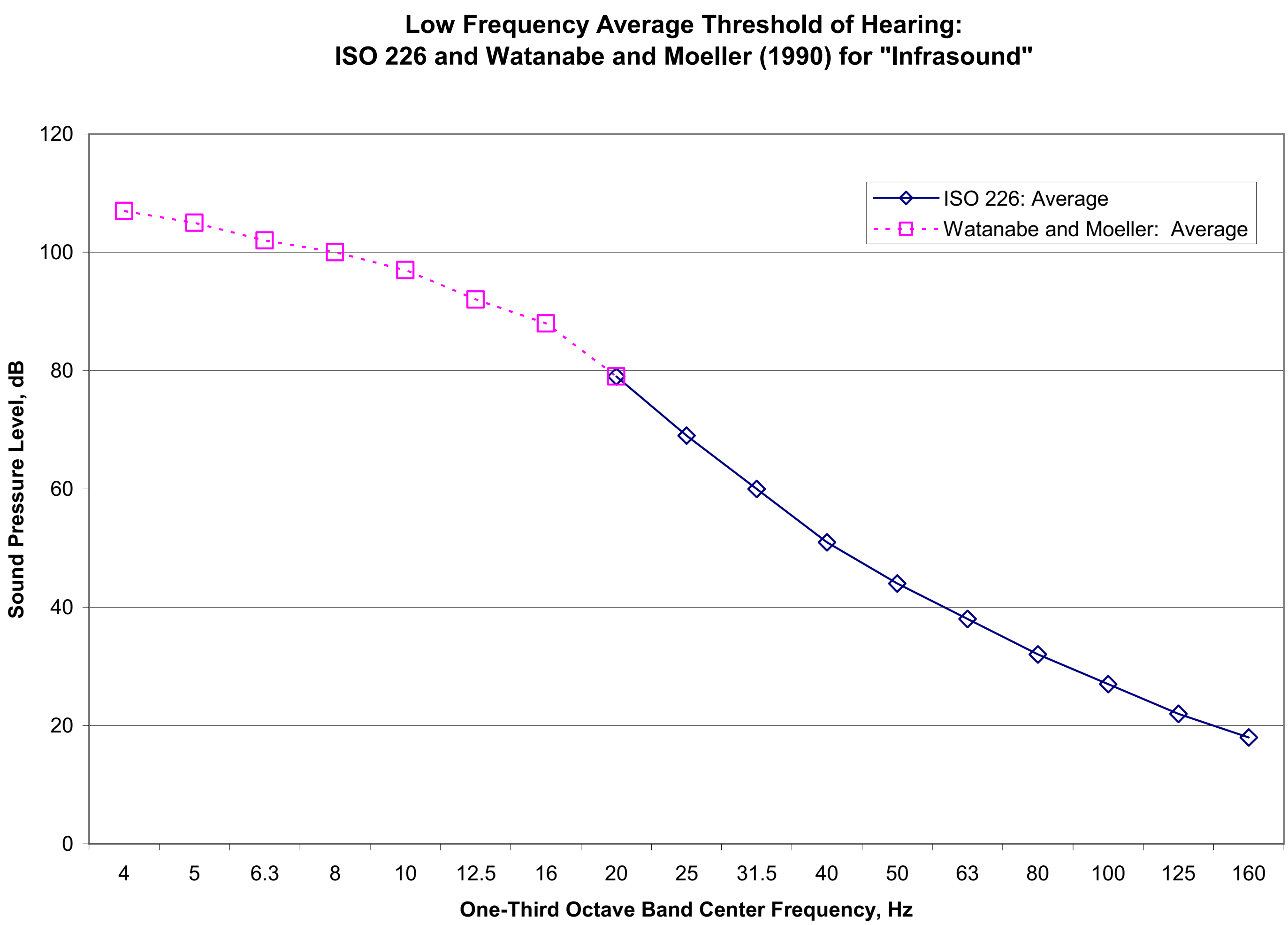
3.2.1 Airborne Vibration

Outdoor low frequency sounds of sufficient amplitude can cause building walls to vibrate and windows to rattle. Homes have low values of transmission loss at low frequencies, and low frequency noise of sufficient amplitude may be audible within homes. Window rattles are not low frequency noise, but may be caused by low frequency noise.

3.2.2 Ground borne Vibration

While not studied nearly as extensively as noise, a few papers were found that examined ground borne vibration from wind turbines (Styles, P. et al, 2005; Hayes McKenzie Partnership, 2006; Gastmeier and Howe (2008)). Measurement of ground borne vibration associated with wind turbine operations were detectable with instruments but were below the threshold of perception, even within the wind farm (Gastmeier and Howe 2008; Snow, D.J., 1997).

Figure 3.1-1 Low Frequency Average Threshold of Hearing



4.0 GUIDELINES AND CRITERIA

4.1 United States Government

There are no specific criteria for low frequency noise in the United States. The US Environmental Protection Agency (EPA) has guidelines for the protection of public health with an adequate margin of safety in terms of annual average A-weighted day-night average sound level (L_{dn}), but there are no corrections or adjustments for low frequency noise. The US Department of Transportation (DOT) has A-weighted sound pressure level criteria for highway projects and airports, but these do not have adjustments for low frequency noise.

4.2 American National Standards (voluntary)

4.2.1 ANSI/ASA S12.9-2007/Part 5

ANSI/ASA S12.9-2007/Part 5 "Quantities and Procedures for description and measurement of environmental sound. Part 5: Sound Level Descriptors for Determination of Compatible Land Use" has an informative annex which provides guidance for designation of land uses compatible with existing or predicted sound levels. The noise metric in ANSI S12.9 Part 5 is the annual average of the adjusted day-night average outdoor sound level (DNL). Ranges of the DNL are outlined, within which a specific region of compatibility may be drawn. These ranges take into consideration the transmission loss in sound level from outside to inside buildings as commonly constructed in that locality and living habits there. There are adjustments to day-night average sound level to account for the presence of low frequency noise, and the adjustments are described in ANSI S12.9 Part 4.

4.2.2 ANSI S12.9-2005/Part 4

ANSI S12.9-2005 Part 4 "Quantities and Procedures for description and measurement of environmental sound. Part 4: Noise assessment and prediction of long-term community response" provides procedures for assessing outdoor environmental sounds and provides for *adjustments* to measured or predicted adjusted annual outdoor day-night A-weighted sound level to account "for the change in annoyance caused by … sounds with strong low-frequency content…"

ANSI S12.9 Part 4 does not specifically define the frequency range for "low-frequency" sounds; however, evaluation methods for low frequency noise in Annex D use a sum of the sound pressure levels in the 16, 31 and 63 Hz octave bands. Procedures apply only when the difference in exterior C-weighted and A-weighted sound levels is greater than 10 dB, ($L_{pC} - L_{pA}$) > 10 dB. Complicated procedures are given for adjustments to L_{Aeq} and L_{dn} values. Adjustments are significant for high levels of low frequency sound.

ANSI S12.9 Part 4 states: "Generally, annoyance is minimal when octave-band sound pressure levels are less than 65 dB at 16, 31.5, and 63-Hz mid-band frequencies. However, low-frequency sound characterized by rapidly fluctuating amplitude … may cause annoyance when these octave-band sound pressure levels are less than 65 dB."

For sounds with strong low-frequency content, adjusted sound exposure level (LNE) is calculated from low-frequency sound pressure level L_{LF} by:

$$\text{LNE} = 2(L_{LF} - 65) + 55 + 10\log(t/1)$$

$$= 2\,L_{LF} - 75 + 10\log(t/1) \qquad \text{(Equation D.1 of ANSI S12.9 Part 4)}$$

where L_{LF} is 10 times the logarithm of the ratio of time-mean square sound pressures in the 16, 31.5, and 63-Hz octave bands divided by the square of the reference sound pressure and

t is the time duration of interest, in seconds, over which the low-frequency sound is present.

The factor of 2 in equation (D.1) accounts for the rapid increase in annoyance with sound pressure level at low frequencies. ANSI S12.9 Part 4 states: "Equation (D.1) also accounts for the additional annoyance from rattles that begins when the low-frequency sound pressure level [L_{LF}] exceeds 75 dB." Later, ANSI S12.9/Part 4 has a contradictory recommendation: "To prevent the likelihood of noise-induced rattles, the low-frequency sound pressure level [L_{LF}] should be less than 70 dB."

ANSI S12.9 /Part 4 identifies two thresholds: annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapidly fluctuations of the low frequency sounds. The second threshold is for increased annoyance which begins when rattles occur, which begins at L_{LF} 70 - 75 dB. Since determination of L_{LF} involves integrating concurrently the sound pressures in the three octave bands, an energy sum of the levels in each of these separate bands results in an upper bound to L_{LF}. (The sound pressure level from the summation of these bands will always be less than L_{LF} since the sound pressures are not in phase within these three bands.)

It should be noted that a recent study on low frequency noise from aircraft operations (Hodgdon, Atchley, Bernhard 2007) reported that an expert panel was critical of using this L_{LF} metric because it had not previously been used to characterize aircraft noise and its reliance on the 16 Hz band since aircraft data does not extend down to 16 Hz and can not be used with the FAA Integrated Noise Model.

The adjustment procedure for low frequency noise to the average annual A-weighted sound pressure level in ANSI S12.9 Part 4 uses a different and more complicated metric and procedure (Equation D.1) than those used for evaluating low frequency noise in rooms contained in ANSI/ASA S12.2. (See section 4.2.3). Since we are evaluating low frequency noise and not A-weighted levels, we do not recommend using the procedure for adjusting A-weighted levels. Instead we recommend using the following two guidelines from ANSI S12.4 Part 9: a sound pressure level of 65 dB in each of the 16-, 31.5-, and 63 Hz octave bands as an indicator of minimal annoyance, and 70 - 75 dB for the summation of the sound pressure levels from these three bands as an indicator of possible increased annoyance from rattles. This method is conservative since the sum of the levels in the three bands will always be less than L_{LF}.

4.2.3 ANSI/ASA S12.2-2008

ANSI/ASA S12.2-2008 discusses criteria for evaluating room noise, and has two separate provisions for evaluating low frequency noise: (1) the potential to cause perceptible vibration and rattles, and (2) meeting low frequency portions of room criteria curves.

Vibration and Rattles: Clause 6 and Table 6 of this standard contain limiting values of sound pressure levels for vibrations and rattles from low frequency noise. The frequency range is not defined, but limiting values and discussion relate only to octave-bands with center frequencies of 16, 31 and 63 Hz. This is the same narrow frequency range from low-frequency sounds as in ANSI S12.9/Part 4. Therefore, ANSI S12.9 Part 4 and ANSI/ASA S12.2 are consistent in evaluating and assessing low frequency sounds both for annoyance (interior and exterior measurements) and vibration (interior measurements) by using sound pressure levels only in the 16, 31 and 63 Hz octave-bands.

ANSI/ASA S12.2 presents limiting levels at low frequencies for assessing (a) the probability of *clearly* perceptible acoustically induced vibration and rattles in lightweight wall and ceiling constructions, and (b) the probability of *moderately* perceptible acoustically induced vibration in similar constructions. These 16, 31.5 and 63 Hz octave band sound pressure level values are presented in Table 4.2-1. One set of values is for when "clearly perceptible vibration and rattles" is likely, and a lower set of values is for when "moderately perceptible vibration and rattles" is likely.

Table 4.2-1 Measured interior sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures. [ANSI/ASA S12.2-2008]

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	75 dB	75 dB	80 dB
Moderately perceptible vibration and rattles likely	65 dB	65 dB	70 dB

Since indoor measurements are not always possible, for comparison to outdoor sound levels the indoor criteria from ANSI/ASA S12.2 should be adjusted. Outdoor to indoor low frequency noise reductions have been reported by Sutherland for aircraft and highway noise for open and closed windows (Sutherland 1978) and by Hubbard for aircraft and wind turbine noise for closed windows (Hubbard 1991). Table 4.2-2 presents the average low frequency octave band noise reductions from outdoor to indoors from these two papers for open and closed windows. Sutherland only reported values down to 63 Hz; whereas Hubbard presented values to less than 10 Hz. The closed window conditions of Hubbard were used to estimate noise reductions less than 63 Hz by applying the difference between values for open and closed windows from Sutherland data at 63 Hz. It should be noted that the attenuation for wind turbines in Hubbard is based on only three homes at two different wind farms, whereas the traffic and aircraft data are for many homes. The wind turbine open window values were obtained from the wind turbine closed window values by subtracting the difference in values between windows closed and open obtained by Sutherland.

Table 4.2-2 Average low frequency octave band noise reductions from outdoor to indoors in dB (based on Sutherland (1978) and Hubbard (1991))

Noise Source	Window condition	Octave Band Center Frequency		
		16 Hz	31.5 Hz	63 Hz
Average aircraft and traffic sources	Closed windows	16	15	18
Average aircraft and traffic sources	Open Windows	(11)*	(10)*	12
Average Wind Turbine	Closed Windows	8	11	14
Average Wind Turbine	**Open Windows**	**(3)*⁺**	**(6)*⁺**	**9⁺**

* No data are available for windows open below 63 Hz octave band. The values for 16 Hz and 31 Hz were obtained by subtracting the difference between the levels for 63 Hz closed and open conditions to the 16 and 31 Hz closed values.

⁺ Used in this report to determine equivalent outdoor criteria from indoor criteria

To be conservative, we use the open window case instead of closed windows. To be further conservative, we use the wind turbine data (adjusted to open windows), which is based on only three homes. However, it should be noted that it is possible for some homes to have some slight amplification at low frequencies with windows open due to possible room resonances. Applying the outdoor to indoor attenuations for wind turbine sources with windows open given in the last row of Table 4.2-2 to the ANSI/ASA S12.2 indoor sound pressure levels in Table 4.2-1 yields the *equivalent* outdoor sound pressure levels that are consistent with the indoor criteria and are presented in Table 4.2-3.

Table 4.2-3 *Equivalent* outdoor sound pressure levels for perceptible vibration and rattle in lightweight wall and ceiling structures based on Tables 4.2-1 and 4.2-2 above for wind turbines.

Condition	Octave-band center frequency (Hz)		
	16	31.5	63
Clearly perceptible vibration and rattles likely	78 dB	81 dB	89 dB
Moderately perceptible vibration and rattles likely	68 dB	71 dB	79 dB

Room Criteria Curves: ANSI/ASA S12.2 has three primary methods for evaluating the suitability of noise within rooms: a survey method - A-weighted sound levels, an engineering method – noise criteria (NC) curves and a method for evaluating low-frequency fluctuating noise using room noise criteria (RNC) curves. "The RNC method should be used to determine noise ratings when the noise from HVAC systems at low frequencies is *loud* and is suspected of containing *sizeable fluctuations or surging*." [emphasis added] The NC curves are appropriate to evaluate low frequency noise from wind turbines in homes since wind turbine noise does not have significant fluctuating low frequency noise sufficient to warrant using RNC curves and since A-weighted sound levels do not adequately determine if there are low frequency problems. [ANSI/ASA S12.2. section 5.3 gives procedures for determining if there are large fluctuations of low frequency noise.]

Annex C.2 of this standard contains recommendations for bedrooms, which are the most stringent rooms in homes: NC and RNC criteria curve between 25 and 30. The recommended NC and RNC criteria for schools and private rooms in hospitals are the same. The values of the sound pressure levels in the 16 – 250 Hz octave bands for NC curves 25 and 30 are shown in Table 4.2-4.

Table 4.2-4 Octave band sound pressure levels for noise criteria curves NC-25 and NC-30. [From Table 1 of ANSI/ASA S12.2]

	Octave-band-center frequency in Hz				
	16	31.5	63	125	250
NC-25	80	65	54	44	37
NC-30	81	68	57	48	41

ANSI/ASA S12.2 also presents a method to determine if the levels below 500 Hz octave band are too high in relation to the levels in the mid-frequencies which could create a condition of "spectrum imbalance". The method for this evaluation is:

- Calculate the speech interference level (SIL) for the measured spectrum. [SIL is the arithmetic average of the sound pressure levels in the 500, 1000, 2000 and 4000 Hz octave bands.] Select the NC curve equal to the SIL value.

- Plot the measured spectra and the NC curve equal to the SIL value on the same graph and determine the differences between the two curves in the octave bands below 500 Hz.

- Estimate the likelihood that the excess low-frequency levels will annoy occupants of the space using Table 4.2-5.

Table 4.2-5 Measured sound pressure level deviations from an NC (SIL) curve that may lead to serious complaints [From ANSI/ASA S12.2:2008].

	Measured Spectrum – NC(SIL), dB			
Octave-band frequency, Hz = >	31.5	63	125	250
Possible serious dissatisfaction	*	6 - 9	6 - 9	6 - 9
Likely serious dissatisfaction	*	>9	>9	>9

*Insufficient data available to evaluate

4.3 Other Criteria

4.3.1 World Health Organization (WHO)

No specific low frequency noise criteria are proposed by the WHO. The Guidelines for Community Noise report (WHO, 1999) mentions that if the difference between dBC and dBA is greater than 10 decibels, then a frequency analysis should be performed to determine if there is a low frequency issue. A document prepared for the World Health Organization states that "there is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for 'normal' sounds. Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter" [Berglund (1995) p. 41]

4.3.2 The UK Department for Environment, Food, and Rural Affairs (DEFRA)

The report prepared by the University of Salford for the UK Department for Environment, Food, and Rural Affairs (DEFRA) on low frequency noise proposed one-third octave band sound pressure level L_{eq} criteria and procedures for assessing low frequency noise [DEFRA (2005)]. The guidelines are based on complaints of disturbance from low frequency sounds and are intended to be used by Environmental Health Officers. Reports by Hayes (2006) and others refer to the proposed criteria as "DEFRA criteria." Tables 4.3-1 and 4.3-2 present the DEFRA criteria for assessment of low frequency noise measured indoors. The criteria are "based on 5 dB below the ISO 226 (2003) average threshold of audibility for steady [low frequency] sounds." However, the DEFRA criteria are at 5 dB lower than ISO 226 only at 20 - 31.5 Hz; at higher frequencies the criteria are equal to the Swedish criteria which are higher levels than ISO 226 less 5 dB. For frequencies lower than 20 Hz, DEFRA uses the thresholds from Watanabe and Moeller (1990) less 5 dB. In developing the DEFRA guidelines, The University of Salford reviewed and considered existing low frequency noise criteria from several European countries.

The DEFRA criteria are based on measurements in an unoccupied room. Hayes Mackenzie (2006) noted that measurements should be made with windows closed; however, we conservatively used windows open conditions for our assessment. If the low frequency sound is "steady" then the criteria may be relaxed by 5 dB. A low frequency noise is considered steady if either of the conditions a) or b) below is met in the third octave band which exceeds the criteria by the greatest margin:

a) L_{10}-L_{90} < 5dB

b) the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second

Applying indoor to outdoor one-third octave band transfer functions for open windows (from analysis in Sutherland (1978) and Hubbard (1991) yields *equivalent* one-third octave band sound pressure level proposed DEFRA criteria for outdoor sound levels. Table 4.3-1 presents both the indoor DEFRA proposed criteria and equivalent proposed criteria for outdoors for non-steady low-frequency sounds. Table 4.3-2 presents the DEFRA proposed criteria for a steady low frequency sound.

Table 4.3-1 DEFRA proposed criteria for the assessment of low frequency noise disturbance: *indoor* and *equivalent outdoor* L_{eq} one-third sound pressure levels for *non-steady* low frequency sounds. [DEFRA (2005)]

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor L_{eq}, dB	92	87	83	74	64	56	49	43	42	40	38	36	34
Equivalent Outdoor L_{eq}, dB	94	89	86	78	68.5	61	56	51	51	49	47	45	43

Table 4.3-2 DEFRA criteria for the assessment of low frequency noise disturbance: *indoor* and *equivalent outdoor* L_{eq} one-third sound pressure levels for *steady* low frequency sounds. [DEFRA (2005)]

Location	One-Third Octave Band Center Frequency, Hz												
	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Indoor L_{eq}, dB	97	92	88	79	69	61	54	48	47	45	43	41	39
Equivalent Outdoor* L_{eq}, dB	99	94	91	83	73.5	66	61	56	56	54	52	50	48

* With windows open

4.3.3 C-weighted minus A-weighted (L_{pC}- L_{pA})

Leventhall (2003) and others indicate that the difference in C-weighted and A-weighted sound pressure levels can be a predictor of annoyance. Leventhall states that if (L_{pC} – L_{pA}) is greater than 20 dB there is "a potential for a low frequency noise problem." He further states that (L_{pC} – L_{pA}) cannot be a predictor of annoyance but is a simple indicator that further analysis may be needed. This is due in part to the fact that the low frequency noise may be inaudible even if (L_{pC} – L_{pA}) is greater than 20 dB.

4.3.4 Threshold of hearing

ISO 226:2003 gives one-third octave band threshold of hearing down to 20 Hz. Watanabe and Moeller (1990) have extended these to 10 Hz and lower, and the values are reported in Moeller and Pedersen (2004). Denmark has established low frequency noise criteria based on audibility. The Danish criteria are "based on hearing thresholds for the 10% most sensitive people in an ontologically unselected population aged 50-60 years. These 10% thresholds are typically about 4-5 dB lower than the average threshold for ontologically normal young adults (18-25 years) as given in ISO 226." [DEFRA (2005)]. Other reports indicate that the standard deviation of these thresholds is also about 5 dB. Table 4.3-3 presents one-third octave band threshold of hearing according to ISO 226 and Watanabe and Moeller. The second row in Table 4.3-3 presents the values that are 5 dB less than the threshold.

Table 4.3-3 Threshold of audibility from ISO 226 and Watanabe and Moeller (1990)

	One-Third Octave band center frequency, Hz																
	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
Threshold	107	105	102	100	97	92	88	79	69	60	51	44	38	32	27	22	18
Threshold – 5 dB	102	100	97	95	92	87	83	74	64	55	46	39	33	27	22	17	13

The average threshold of hearing values in Table 4.3-3 are also shown in Figure 3.1-1.

4.3.5 Ground-Borne Vibration

ANSI S2.71-1983 (formerly ANSI S3.29-1983) presents recommendations for magnitudes of ground-borne vibration which humans will perceive and possibly react to within buildings. A basic rating is given for the most stringent conditions, which correspond to the approximate threshold of perception of the most sensitive humans. From the base rating, multiplication factors should be applied according to the location of the receiver; for continuous sources of vibration in residences at nighttime, the multiplication factor is 1.0 – 1.4.

ANSI S2.71-1983 presents one-third octave band acceleration or velocity ratings for z-axis, and x-, y-axis vibrations. For spaces in which the occupants may be sitting, standing, or lying at various times, the standard recommends using a combined axis rating which is obtained from the most stringent rating for each axis. Measurements in each of the 3 axes should be compared to the combined axis rating. Table 4.3-4 presents the base response velocity ratings for the combined axis. The velocity ratings are for root-mean-square (RMS) values.

Table 4.3-4 Base response one-third octave band RMS velocity ratings for the three biodynamic vibration axes and combined axis (From ANSI S2.71-1983 (R2006)

One-Third Octave band center frequency, Hz	Velocity (RMS), m/s		
	z axis	x, y axis	Combined axis
1	1.6×10^{-3}	5.7×10^{-4}	5.7×10^{-4}
1.25	1.1×10^{-3}	4.6×10^{-4}	4.6×10^{-4}
1.6	8.0×10^{-4}	3.6×10^{-4}	3.6×10^{-4}
2	5.6×10^{-4}	2.9×10^{-4}	2.9×10^{-4}
2.5	4.0×10^{-4}	2.9×10^{-4}	2.4×10^{-4}
3.15	2.9×10^{-4}	2.9×10^{-4}	2.1×10^{-4}
4	2.0×10^{-4}	2.9×10^{-4}	1.7×10^{-4}
5	1.6×10^{-4}	2.9×10^{-4}	1.4×10^{-4}
6.3	1.3×10^{-4}	2.9×10^{-4}	1.2×10^{-4}
8	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
10	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
12.5	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
16	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
20	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
25	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
31.5	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
40	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
50	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
63	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}
80	1.0×10^{-4}	2.9×10^{-4}	1.0×10^{-4}

5.0 LITERATURE REVIEW

Epsilon performed an extensive literature search of over 100 scientific papers, technical reports and summary reports on low frequency sound and infrasound - hearing, effects, measurement, and criteria. The following paragraphs briefly summarize the findings from some of these papers and reports.

5.1 H. Moeller and C. S. Pedersen (2004)

Moeller and Pedersen (2004) present a comprehensive summary on hearing and non-auditory perception of sound at low and infrasonic regions, some of which has been cited in sections 3.1.1, 3.1.2, and 3.1.3 of this report.

5.2 Leventhall (2003)

Leventhall presents an excellent study on low frequency noise from all sources and its effects. The report presents criteria in place at that time. Included are figures and data relating cause and effects.

5.3 Leventhall (2006)

Leventhall reviewed data and allegations on alleged problems from low frequency noise and infrasound from wind turbines. Leventhall concluded the following: "It has been shown that there is insignificant infrasound from wind turbines and that there is normally little low frequency noise." "Turbulent air inflow conditions cause enhanced levels of low frequency noise, which may be disturbing, but the overriding noise from wind turbines is the fluctuating audible swish, mistakenly referred to as "infrasound" or "low frequency noise". "Infrasound from wind turbines is below the audible threshold and of no consequence". Other studies have shown that wind turbine generated infrasound levels are below threshold of perception and threshold of feeling and body reaction.

5.4 Delta (2008)

The Danish Energy Authority project on "low frequency noise from large wind turbines" comprises a series of investigations in the effort to give increased knowledge on low frequency noise from wind turbines. One of the conclusions of the study is that wind turbines do not emit audible infrasound, with levels that are "far below the hearing threshold." Audible low frequency sound may occur both indoors and outdoors, "but the levels in general are close to the hearing and/or masking level." "In general the noise in the critical band up to 100 Hz is below both thresholds". The summary report notes that for road traffic noise (in the vicinity of roads) the low frequency noise levels are higher [than wind turbine] both indoors and outdoors.

5.5 Hayes McKenzie (2006)

Hayes McKenzie performed a study for the UK Department of Trade & Industry (DTI) to investigate complaints of low frequency noise that came from three of the five farms with complaints out of 126 wind farms in the UK. The study concluded that:

- ♦ Infrasound associated with modern wind turbines is not a source which will result in noise levels that are audible or which may be injurious to the health of a wind farm neighbor.
- ♦ Low frequency noise was measureable on a few occasions, but below DEFRA criteria. Wind turbine noise may result in indoor noise levels within a home that is just above the threshold of audibility; however, it was lower than that of local road traffic noise.
- ♦ The common cause of the complaints was not associated with low frequency noise but the occasional audible modulation of aerodynamic noise, especially at night. Data collected indoors showed that the higher frequency modulated noise levels were insufficient to awaken the residents at the three sights; however, once awake, this noise could result in difficulties in returning to sleep.

The UK Department of Trade and Industry, which is now the UK Department for Business Enterprise and Regulatory Reform (BERR), summarized the Hayes McKenzie report: "The report concluded that there is no evidence of health effects arising from infrasound or low frequency noise generated by wind turbines." [BERR (2007)]

5.6 Howe (2006)

Howe performed extensive studies on wind turbines and infrasound and concluded that infrasound was not an issue for modern wind turbine installations – "while infrasound can be generated by wind turbines, it is concluded that infrasound is not of concern to the health of residences located nearby." Since then Gastmeier and Howe (2008) investigated an additional situation involving the alleged "perception of infrasound by individual." In this additional case, the measured indoor infrasound was at least 30 dB below the perception threshold given by Watanabe and Moeller (1990) as presented in Table 4.3-3. Gastmeier and Howe (2008) also performed vibration measurements at the residence and nearest wind turbine, and concluded that the vibration levels were well below the perception limits discussed in ISO 2631-2.

5.7 Branco (2004)

Branco and other Portuguese researchers have studied possible physiological affects associated with high amplitude low frequency noise and have labeled these alleged effects as “Vibroacoustic Disease” (VAD). “Vibroacoustic disease (VAD) is a whole-body, systemic pathology, characterized by the abnormal proliferation of extra-cellular matrices, and caused by excessive exposure to low frequency noise.” Hayes (2007, 2008) concluded that levels from wind farms are not likely to cause VAD after comparing noise levels from alleged VAD cases to noise levels from wind turbines in homes of complainers. Noise levels in aircraft in which VAD has been hypothesized are considerably higher than wind turbine noise levels. Hayes also concluded that it is “unlikely that symptoms will result through induced internal vibration from incident wind farm noise.” [Hayes (2007)] Other studies have found no VAD indicators in environmental sound that have been alleged by VAD proponents. [ERG (2001)]

5.8 French National Academy of Medicine (2006)

French National Academy of Medicine recommended “*as a precaution* construction should be suspended for wind turbines with a capacity exceeding 2.5 MW located within 1500 m of homes.” [emphasis added] However, this precaution is not because of definitive health issues but because:

- sound levels one km from some wind turbine installations “occasionally exceed allowable limits” for France (note that the allowable limits are long term averages)
- French prediction tools for assessment did not take into account sound levels created with wind speeds greater than 5 m/s.
- Wind turbine noise has been compared to aircraft noise (even though the sound levels of wind turbine noise are significantly lower), and exposure to high level aircraft noise “involves neurobiological reactions associated with an increased frequency of hypertension and cardiovascular illness. Unfortunately, no such study has been done near wind turbines.” [Gueniot (2006)].

In March 2008, the French Agency for Environmental and Occupational Health Safety (AFSSET) published a report on “the health impacts of noise generated by wind turbines”, commissioned by the Ministries of Health and Environment in June 2006 following the report of the French National Academy of Medicine in March 2006. [AFSSET (2008)] The AFSSET study recommends that one does not define a fixed distance between wind farms and homes, but rather to model the acoustic impact of the project on a case-by-case basis. One of the conclusions of the AFSSET report is: "The analysis of available data shows: The absence of identified direct health consequences concerning the auditory effects or specific effects usually associated with exposure to low frequencies at high level.” (“L'analyse des données disponibles met en évidence: L'absence de conséquences sanitaires directes recensées en ce qui concerne les effets auditifs, ou les effets spécifiques généralement attachés à l'exposition à des basses fréquences à niveau élevé.”)

6.0 REPRESENTATIVE WIND TURBINES

At the direction of NextEra, two types of utility-scale wind turbines were studied:

- General Electric (GE) 1.5sle (1.5 MW), and
- Siemens SWT-2.3-93 (2.3 MW).

Typical hub height for these wind turbines is 80 meters above ground level (AGL).

Sound levels for these wind turbine generators (WTGs) vary as a function of wind speed from cut-in wind speed to maximum sound level. Table 6.0-1 below lists the reference sound power levels of each WTG as a function of wind speed at 10 meters AGL as provided by the manufacturer. This is in conformance with the sound level standard for wind turbines [IEC 61400-11].

Table 6.0-1 Sound power levels as a Function of Wind Speed (dBA)

Wind Speed at 10 meters AGL (m/s)	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
3	< 96	ND
4	< 96	ND
5	99.1	99
6	103.0	103.4
7	≤104	104.9
8	≤104	105.1
9	≤104	105.0
10	≤104	105.0

ND = No Data available

Each wind turbine manufacturer applied the uncertainty factor K of 2 dBA to guarantee the turbine's sound power level. (According to IEC TS 61400-14, K accounts for both measurement variations and production variation.) The results in Section 8.0 use the manufacturer's guaranteed value, that is, 2 dBA above the levels in Table 6.0-1.

One-third octave band sound power level data have also been provided for each turbine reflective of the highest A-weighted level (typically a wind speed of 8 m/s or greater at 10 m AGL). These data are reference (not guaranteed) data, and are summarized below in Table 6.0-2. Cut-in wind speed for the GE 1.5 sle wind turbine is 3.5 m/s while the Siemens wind turbine has a cut-in wind speed of 4 m/s. The last two rows in Table 6.0-2 contain the overall A-weighted sound power levels from Table 6.0-1 and the guaranteed values.

Table 6.0-2 One-Third Octave Sound Power Levels at 8 m/s (un-weighted, dB)

1/3 Octave Band Center Frequency, Hz	GE 1.5 sle 80 m hub height; 77 m rotor diameter	Siemens SWT-2.3-93 80 m hub height; 92.4 m rotor diameter
25	ND	109.0
31.5	ND	105.7
40	ND	105.3
50	106.4	105.3
63	106.1	104.8
80	105.1	104.7
100	103.9	104.8
125	102.8	105.3
160	105.8	103.2
200	101.6	103.7
250	100.6	105.0
315	100.6	102.5
400	99.1	100.2
500	97.0	97.8
630	95.1	95.8
800	94.8	93.5
1000	92.8	92.7
1250	91.7	90.6
1600	90.5	88.2
2000	88.4	87.1
2500	85.8	85.6
3150	83.6	83.9
4000	81.2	82.1
5000	78.1	80.8
6300	76.0	79.9
8000	72.4	79.4
10000	73.3	80.0
Overall - Reference	104 dBA	105 dBA
Guaranteed	106 dBA	107 dBA

ND = No data provided.

7.0 FIELD PROGRAM

Real-world data were collected from operating wind turbines to compare to the low frequency noise guidelines and criteria discussed previously in Section 4.0. These data sets consisted of outdoor measurements at various reference distances, and concurrent indoor/outdoor measurements at residences within the wind farm. Epsilon determined all means, methods, and the testing protocol without interference or direction from NextEra. No limitations were placed on Epsilon by NextEra with respect to the testing protocol or upon the analysis methods.

7.1 GE 1.5sle and Siemens SWT-2.3-93

Field measurements were conducted in order to measure sound levels at operating wind turbines, and compare them to the guidelines and criteria discussed in this report. NextEra provided access to the Horse Hollow Wind Farm in Taylor and Nolan Counties, Texas in November 2008 to collect data on the GE 1.5 sle and Siemens SWT-2.3-93 wind turbines. The portion of the wind farm used for testing is relatively flat with no significant terrain. The land around the wind turbines is rural and primarily used for agriculture and cattle grazing. The siting of the sound level measurement locations was chosen to minimize local noise sources except the wind turbines and the wind itself.

Two noise consultants collected sound level and wind speed data over the course of one week under a variety of operational conditions. Weather conditions were dry the entire week with ground level winds ranging from calm to 28 mph (1-minute average). In order to minimize confounding factors, the data collection tried to focus on periods of maximum sound levels from the wind turbines (moderate to high hub height winds) and light to moderate ground level winds.

Ground level (2 meters AGL) wind speed and direction were measured continuously at one representative location. Wind speeds near hub height were also measured continuously using the permanent meteorological towers maintained by the wind farm.

A series of simultaneous interior and exterior sound level measurements were made at four houses owned by participating landowners within the wind farm. Two sets were made of the GE WTGs, and two sets were made of the Siemens WTGs. Data were collected with both windows open and windows closed. Due to the necessity of coordinating with the homeowners in advance, and reasonable restrictions of time of day to enter their homes, the interior/exterior measurement data sets do not always represent ideal conditions. However, enough data were collected to compare to the criteria and draw conclusions on low frequency noise.

Sound level measurements were also made simultaneously at two reference distances from a string of wind turbines under a variety of wind conditions. Using the manufacturer's sound level data discussed in Section 6.0, calculations of the sound pressure levels as a function of distance in flat terrain were made to aid in deciding where to collect data in the field. Based on this analysis, two distances from the nearest wind turbine were selected - 1000 feet and 1500 feet - and were then used where possible during the field program.

Distances much larger than 1,500 feet were not practical since an adjacent turbine string could be closer and affect the measurements, or would put the measurements beyond the boundaries of the wind farm property owners. Brief background sound level measurements were conducted several times during the program whereby the Horse Hollow Wind Farm operators were able to shutdown the nearby WTGs for a brief (20 minutes) period. This was done in real time using cell phone communication.

All the sound level measurements described above were attended by the noise consultants. One series of unattended overnight measurements was made at two locations for approximately 15 hours to capture a larger data set. One measurement was set up approximately 1,000 feet from a GE 1.5 sle WTG and the other was set up approximately 1,000 feet from a Siemens WTG. The location was chosen based on the current wind direction forecast so that the sound level equipment would be downwind for the majority of the monitoring period. By doing this, the program was able to capture periods of strong hub-height winds and moderate to low ground-level winds.

Ground-borne vibration measurements were made within the Horse Hollow Wind Farm. Measurements were made 400 feet and 1000 feet downwind from both GE 1.5 sle and Siemens 2.3 MW WTGs under full operation. In addition, background vibration measurements were made with the WTGs briefly shutdown.

7.2 Measurement Equipment

Ground level wind speed and direction were measured with a HOBO H21-002 micro weather station (Onset Computer Corporation). The data were sampled every three seconds and logged every one minute. All sound levels were measured using two Norsonic Model Nor140 precision sound analyzers, equipped with a Norsonic-1209 Type 1 Preamplifier, a Norsonic-1225 half-inch microphone and a 7-inch Aco-Pacific untreated foam windscreen Model WS7. The instrumentation meets the "Type 1 - Precision" requirements set forth in American National Standards Institute (ANSI) S1.4 for acoustical measuring devices. The microphone was tripod-mounted at a height of five feet above ground. The measurements included simultaneous collection of broadband (A-weighted) and one-third-octave band data (0.4 hertz to 20,000 hertz bands). Sound level data were primarily logged in 10-minute intervals to be consistent with the wind farm's Supervisory Control And Data Acquisition (SCADA) system which provides power output (kW) in 10-minute increments. A few sound level measurements were logged using 20-miute intervals. The meters were calibrated and certified as accurate to standards set by the National Institute of Standards and Technology. These calibrations were conducted by an independent laboratory within the past 12 months.

The ground-borne vibration measurements were made using an Instantel Minimate Plus vibration and overpressure monitor. A triaxial geophone inserted in the ground measured the particle velocity (PPV). Each measurement was 20 seconds in duration and all data were stored in memory for later retrieval.

8.0 RESULTS AND COMPARISON TO CRITERIA

Results from the field program are organized by wind turbine type. For each wind turbine type, results are presented per location type (outdoor or indoor) with respect to applicable criteria. Results are presented for 1,000 feet from the nearest wind turbine. Data were also collected at 1,500 feet from the nearest wind turbine which showed lower sound levels. Therefore, wind turbines that met the criteria at 1,000 feet also met it at 1,500 feet. Data were collected under both high turbine output and moderate turbine output conditions, and low ground-level wind speeds (defined as sound power levels 2 or 3 dBA less than the maximum sound power levels). The sound level data under the moderate conditions were equivalent to or lower than the high turbine output scenarios, thus confirming the conclusions from the high output cases. A-weighted sound power levels presented in this section (used to describe turbine operation) were estimated from the actual measured power output (kW) of the wind turbines and the sound power levels as a function of wind speed presented in Table 6.0-1 plus an adjustment factor of 2 dBA (correction from reference values to guaranteed values).

Outdoor measurements are compared to criteria for audibility, for UK DEFRA disturbance using equivalent outdoor levels, for rattle and annoyance criteria as contained in ANSI S12.9 Part 4, and for perceptible vibration using equivalent outdoor levels from ANSI/ASA S12.2. Indoor measurements are compared to criteria for audibility, for UK DEFRA disturbance, and for suitability of bedrooms, hospitals and schools and perceptible vibration from ANSI/ASA S12.2.

8.0.1 Audibility

The threshold of audibility criteria discussed in section 4.3.4 is used to evaluate wind turbine sound levels. The audibility of wind turbines both outdoors and indoors was examined.

8.0.2 UK DEFRA Disturbance Criteria

The DEFRA one-third octave band sound pressure level L_{eq} criteria and procedures for assessing disturbance from low frequency noise (see section 4.3.2) were examined. The indoor criteria and equivalent outdoor criteria were compared to measured low frequency noise from wind turbines.

8.0.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

The ANSI/ASA S12.2 interior perceptible vibration criteria were converted to equivalent outdoor criteria as discussed in section 4.2.3 and compared to the measured low frequency noise from wind turbines. In addition, measured data were compared to ANSI S12.9 Part 4 low frequency sound levels for minimal annoyance and for the threshold for beginning of rattles as described in section 4.2.2.

8.0.4 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

The ANSI/ASA S12.2 interior perceptible vibration criteria and low frequency portions of the room criteria for evaluating the suitability of noises in bedrooms, hospitals and schools were compared to indoor measurements of low frequency noise from wind turbines. (See section 4.2.3.)

8.1 Siemens SWT-2.3-93

8.1.1 Outdoor Measurements - Siemens SWT-2.3-93

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest Siemens WTG. This site was actually part of a string of 15 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-1

Table 8.1-1 Summary of Operational Parameters – Siemens SWT-2.3-93 (Outdoor)

Parameter	Sample #34	Sample #39
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	22:00-22:10	22:50-23:00
WTG power output	1,847 kW	1,608 kW
Sound power	107 dBA	106.8 dBA
Measured wind speed @ 2 m	3.3 m/s	3.4 m/s
L_{Aeq}	49.4 dBA	49.6 dBA
L_{A90}	48.4 dBA	48.6 dBA
L_{Ceq}	63.5 dBC	63.2 dBC

8.1.1.1 Outdoor Audibility

Figure 8.1-1 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

8.1.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.1-2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met.

8.1.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.1-3 plots the 16, 31.5, and 63 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 31.5 and 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4, and the 16 Hz sound level is within 1.5 dB of this level, which is an insignificant increase since the levels were not rapidly fluctuating.

8.1.2 Indoor Measurements - Siemens SWT-2.3-93

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from Siemens WTGs. In each house measurements were made in a room facing the wind turbines, and were made with either window open or closed. These residences are designated Homes "A" and "D" and were approximately 1,000 feet from the closest Siemens WTG. Both homes were near a string of multiple WTGS, four of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.1-2.

Table 8.1-2 Summary of Operational Parameters – Siemens SWT-2.3-93 (Indoor)

Parameter	Home "A" (closed / open)	Home "D" (closed / open)
Distance to nearest WTG	1,060 feet	920 feet
Time of day	7:39-7:49 / 7:51-8:01	16:16-16:26 / 16:30 -16:40
WTG power output	1,884 kW / 1564 kW	2,301 kW / 2299 kW
Sound power	107 dBA / 106.7 dBA	107 dBA / 107 dBA
Measured wind speed @ 2 m	3.2 m/s / 3.7 m/s	9.6 m/s / 8.8 m/s
L_{Aeq}	33.8 dBA /38.1 dBA	35.0 dBA / 36.7 dBA
L_{A90}	28.1 dBA / 36.8 dBA	29.6 dBA / 31.2 dBA
L_{Ceq}	54.7 dBC / 57.1 dBC	52.8 dBC / 52.5 dBC

8.1.2.1 Indoor Audibility

Figure 8.1-4a plots the indoor one-third octave band sound levels (L_{eq}) for Home "A", and Figure 8.1-4b plots the indoor one-third octave band sound levels for Home "D". The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at or above 50 Hz may be audible depending on background sound levels.

8.1.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.1-5a plots the indoor one-third octave band sound levels (L_{eq}) for Home "A". The low frequency sound was "steady" according to DEFRA procedures, and the results show that all outdoor equivalent DEFRA disturbance criteria are met. Figure 8.1-5b plots the indoor one-third octave band sound levels (L_{eq}) for Home "D". According to DEFRA procedures, the low frequency sound was not "steady" and therefore the data were compared to both criteria. The results show the DEFRA disturbance criteria were met for steady low frequency sounds, the DEFRA criteria were met for unsteady low frequency sounds except for the 125 Hz band, which was within 1 dB, which is an insignificant difference.

8.1.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.1-6a plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "A", and Figure 8.1-6b plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "D". The results show the ANSI/ASA S12.2 low frequency criteria were easily met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

8.2 GE 1.5sle

8.2.1 Outdoor Measurements - GE 1.5sle

Several periods of high wind turbine output and relatively low ground wind speed (which minimized effects of wind noise) were measured outdoors approximately 1,000 feet from the closest GE 1.5 sle WTG. This site was actually part of a string of more than 30 WTGS, four of which were within 2,000 feet of the monitoring location. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters for these measurements are listed in Table 8.2-1.

Table 8.2-1 Summary of Operational Parameters – GE 1.5sle (Outdoor)

Parameter	Sample #46	Sample #51
Distance to nearest WTG	1,000 feet	1,000 feet
Time of day	23:10-23:20	00:00-00:10
WTG power output	1,293 kW	1,109 kW
Sound power	106 dBA	106 dBA
Measured wind speed @ 2 m	4.1 m/s	3.3 m/s
L_{Aeq}	50.2 dBA	50.7 dBA
L_{A90}	49.2 dBA	49.7 dBA
L_{Ceq}	62.5 dBC	62.8 dBC

8.2.1.1 Outdoor Audibility

Figure 8.2-1 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 31.5 - 40 Hz may be audible depending on background sound levels.

8.2.1.2 UK DEFRA Disturbance Criteria – Outdoor measurements

Figure 8.2-2 plots the one-third octave band sound levels (L_{eq}) for both samples of high output conditions. The low frequency sound was "steady" according to DEFRA procedures, and the results show the low frequency sound meet or are within 1 dB of outdoor equivalent DEFRA disturbance criteria.

8.2.1.3 Perceptible Vibration, Rattle and Annoyance – Outdoor Measurements

Figure 8.2-3 plots the 16, 31.5, and 63 Hz octave band sound levels (L_{eq}) for both samples of high output conditions. The results show that all outdoor equivalent ANSI/ASA S12.2 perceptible vibration criteria are met. The low frequency sound levels are below the ANSI S12.9 Part 4 thresholds for the beginning of rattles (16, 31.5, 63 Hz total less than 70 dB), and the 16, 31.5, 63 Hz sound levels are below the level of 65 dB identified for minimal annoyance in ANSI S12.9 Part 4.

8.2.2 Indoor Measurements - GE 1.5sle

Simultaneous outdoor and indoor measurements were made at two residences at different locations within the wind farm to determine indoor audibility of low frequency noise from GE 1.5sle WTGs. In each house, measurements were made in a room facing the wind turbines, and were made with window either open or closed. These residences are designated Homes "B" and "C" and were approximately 1,000 feet from the closest Siemens WTG. Operational conditions were maximum turbine noise and high ground winds at Home "B", and within 1.5 dBA of maximum turbine noise and high ground level winds at Home "C". Home "B" was near a string of multiple WTGs, four of which were within 2,000 feet of the house, while Home "C" was at the end of a string of WTGs, two of which were within 2,000 feet of the house. The sound level data presented herein include contributions from all wind turbines as measured by the recording equipment. The key operational and meteorological parameters during these measurements are listed in Table 8.2-2.

Table 8.2-2 Summary of Operational Parameters – GE 1.5sle (Indoor)

Parameter	Home "B" (closed / open)	Home "C" (closed / open)
Distance to nearest WTG	950 feet	1,025 feet
Time of day	9:29-9:39 / 9:40-9:50	11:49-11:59 / 12:00-12:10
WTG power output	1,017 kW / 896 kW	651 kW / 632 kW
Sound power	106 dBA / 105.8 dBA	104.7 dBA / 104.6 dBA
Measured wind speed @ 2 m	6.2 m/s / 6.8 m/s	6.4 m/s / 5.9 m/s
L_{Aeq}	27.1 dBA / 36.0 dBA	33.6 dBA / 39.8 dBA
L_{A90}	23.5 dBA / 33.7 dBA	27.6 dBA / 34.2 dBA
L_{Ceq}	47.1 dBC / 54.4 dBC	50.6 dBC / 55.1 dBC

8.2.2.1 Indoor Audibility

Figure 8.2-4a plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-4b plots the indoor one-third octave band sound levels for Home "C". The results show that infrasound is inaudible to even the most sensitive people 1,000 feet from these wind turbines with the windows open or closed (more than 20 dB below the median thresholds of hearing). Low frequency sound at and above 63 Hz may be audible depending on background sound levels.

8.2.2.2 UK DEFRA Disturbance Criteria – Indoor Measurements

Figure 8.2-5a plots the indoor one-third octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-5b plots the indoor one-third octave band sound levels (L_{eq}) for Home "C". The results show the DEFRA disturbance criteria were met for steady and non-steady low frequency sounds.

8.2.2.3 ANSI/ASA S12.2 Low Frequency Criteria – Indoor Measurements

Figure 8.2-6a plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "B", and Figure 8.2-6b plots the indoor 16 Hz to 125 Hz octave band sound levels (L_{eq}) for Home "C". The results show the ANSI/ASA S12.2 low frequency criteria were met for both windows open and closed scenarios. The ANSI/ASA S12.2 low frequency criteria for bedrooms, classrooms and hospitals were met, the spectrum was balanced, and the criteria for moderately perceptible vibrations in light-weight walls and ceilings were also met.

8.3 Noise Reduction from Outdoor to Indoor

Simultaneous outdoor and indoor measurements were made at four residences within the Horse Hollow Wind Farm to determine noise reductions of the homes for comparison to that used in the determination of equivalent outdoor criteria for indoor criteria, such as ANSI/ASA S12.2 and DEFRA. Indoor measurements were made with windows open and closed. Tables 8.1-2 and 8.2-2 list the conditions of measurement for these houses.

The outdoor sound level data at Home "D" was heavily influenced by high ground winds – the measured levels were higher due to the effect of the wind on the microphone or the measurement of wind effect noise; therefore the data from Home "D" was not used in the comparison of noise reduction, since it would over estimate actual noise reduction.

Figures 8.3-1a and 8.3-1b present the measured one-third octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in these same figures are the one-third octave noise reductions used in Section 4 of this report to obtain equivalent outdoor criteria for the indoor DEFRA criteria ("Table 4.3-1 Noise Reduction - Open Window"). It can be seen that for the window closed condition in Figure 8.3-1a, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 25 Hz had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 25 Hz at each of these home was significantly lower than the indoor DEFRA criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor DEFRA criteria at 25 Hz.

Table 8.3-1 presents the measured octave band noise reduction for the three homes with windows closed and open, respectively. Also presented in Table 8.3-1 are the octave band noise reductions used in Table 4.2-2 of this report to obtain equivalent outdoor criteria for the indoor ANSI/ASA S12.2 criteria for perceptible vibration. It can be seen that for the window closed condition, the measured noise reductions for all houses were greater than that used in our analysis as described in Section 4. For the open window case, the average of the three homes has a greater noise reduction than used in Section 4 and all houses at all frequencies have higher values with one minor exception. Only Home "A" at 31 Hz (which contains the 25 Hz one-third octave band) had a lower noise reduction (3dB), and this difference is not critical since the measured indoor sounds at 31 Hz at each of these homes was significantly lower than the indoor ANSI/ASA S12.2 criteria. Furthermore, the outdoor measurements for both Siemens and GE wind turbines at 1000 feet under high output/high noise levels met the equivalent outdoor ANSI/ASA S12.2 criteria at 31 Hz.

Table 8.3-1 Summary of Octave Band Noise Reduction – Interior Measurements

Home	Wind Turbine	Windows	16 Hz	31.5 Hz	63 Hz
A	Siemens SWT-2-3-93	Closed	5	6	16
A	Siemens SWT-2-3-93	Open	4	3	12
B	GE 1.5 sle	Closed	20	22	22
B	GE 1.5 sle	Open	13	17	18
C	GE 1.5 sle	Closed	13	14	19
C	GE 1.5 sle	Open	8	13	17
Table 4.2-2 Noise Reduction		Open	3	6	9

8.4 Ground-Borne Vibration

Seven sets of ground-borne vibration measurements were made from Siemens 2.3 and GE 1.5sle wind turbines. The maximum ground-borne vibration RMS particle velocities were 0.071 mm/second (0.0028 inches/second) in the 8 Hz one-third octave band. This was measured 1000 feet downwind from a GE 1.5sle WTG under maximum power output and high wind at the ground. The background ground-borne vibration RMS particle velocity at the same location approximately 20 minutes beforehand was 0.085 mm/sec. Both of these measurements meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours. Soil conditions were soft earth representative of an active agricultural use. These vibration levels are nearly three orders of magnitude below the level of 0.75 inches/second set to prevent damage to residential structures. No perceptible vibration was felt from operation of the wind turbines. Measurements at the other sites and as close as 400 feet were significantly lower than the above measurements under high wind conditions.

Figure 8.1-1 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

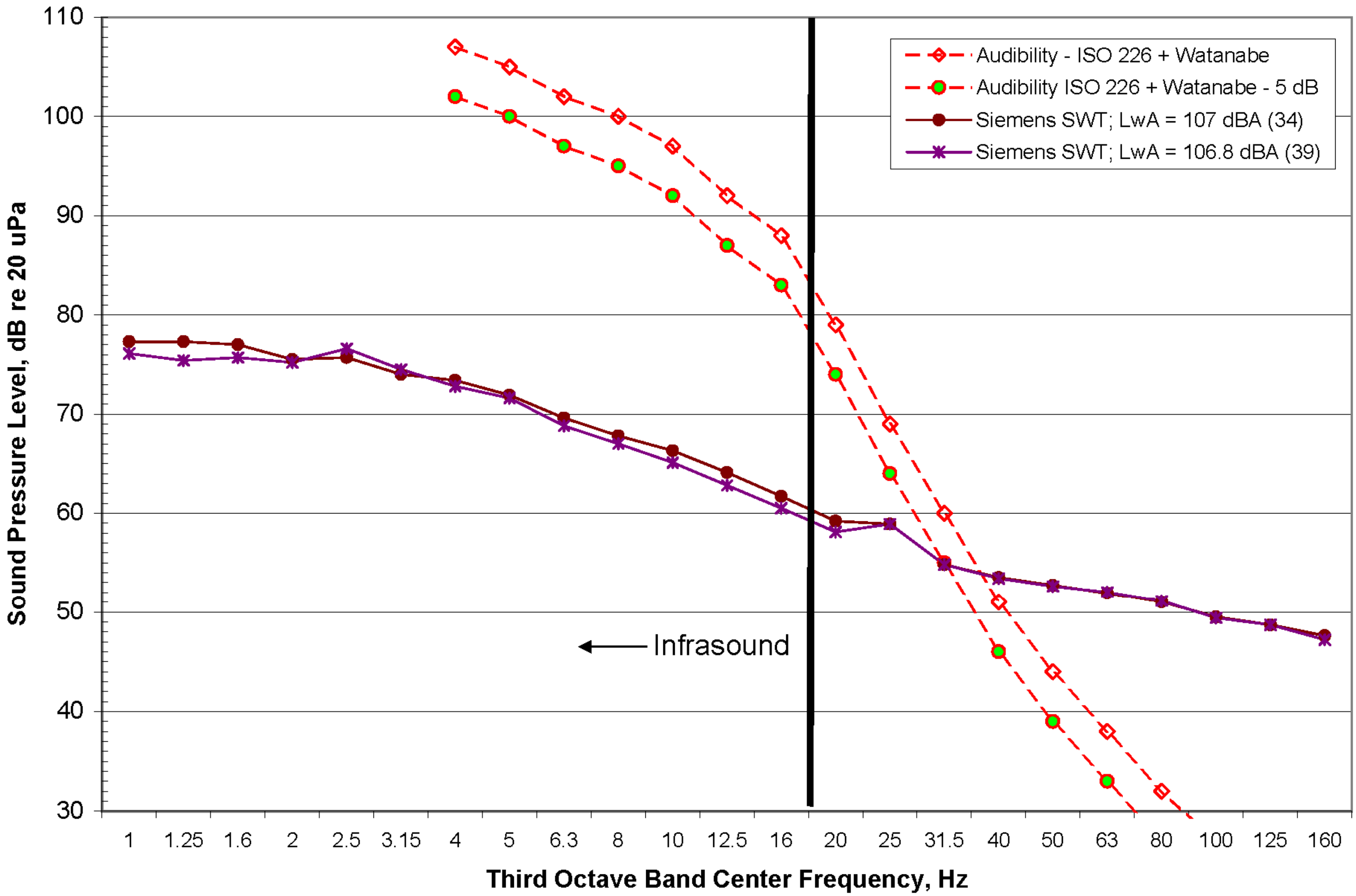


Figure 8.1-2 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

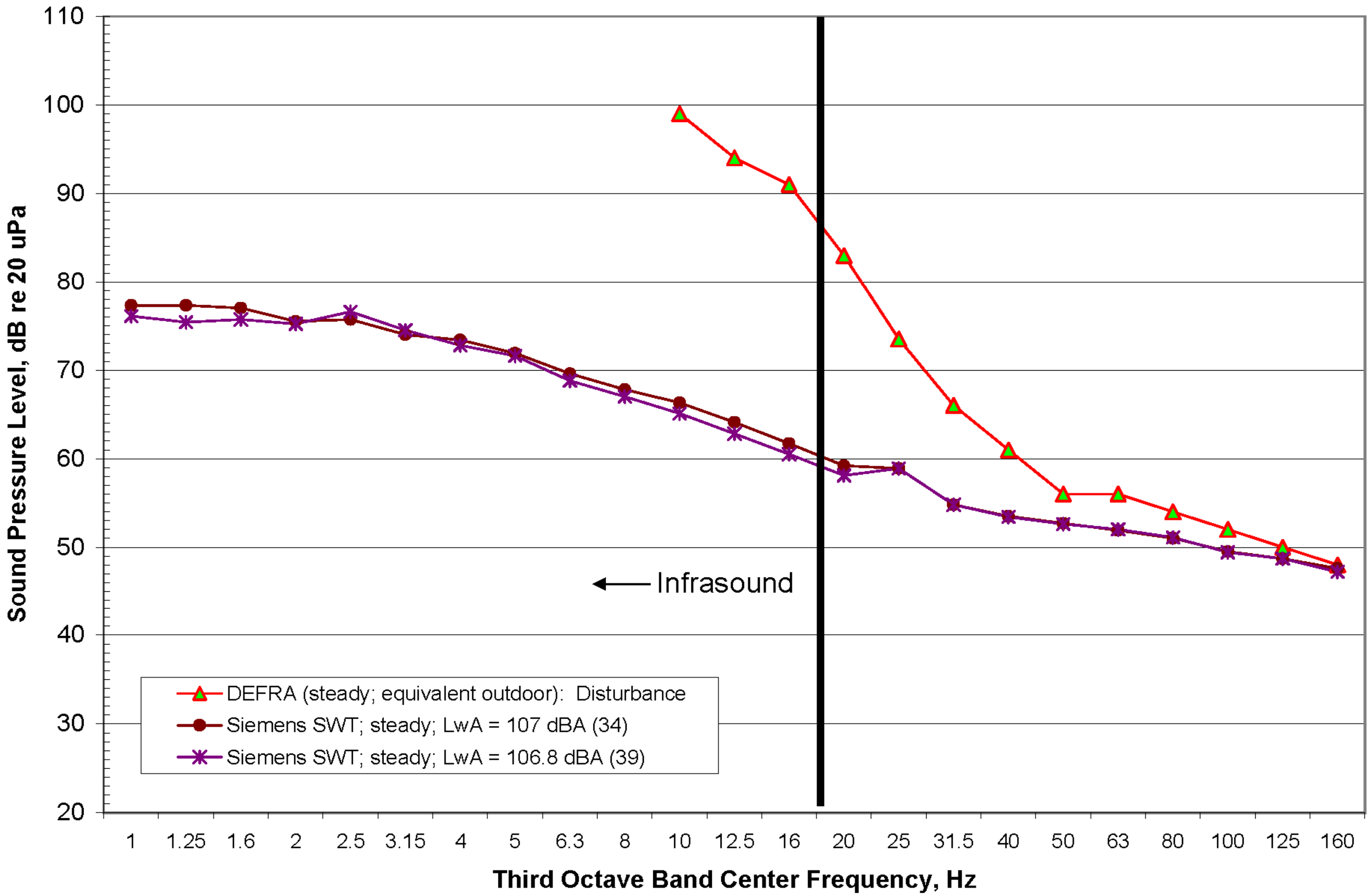


Figure 8.1-3 Siemens SWT-2.3-93 Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

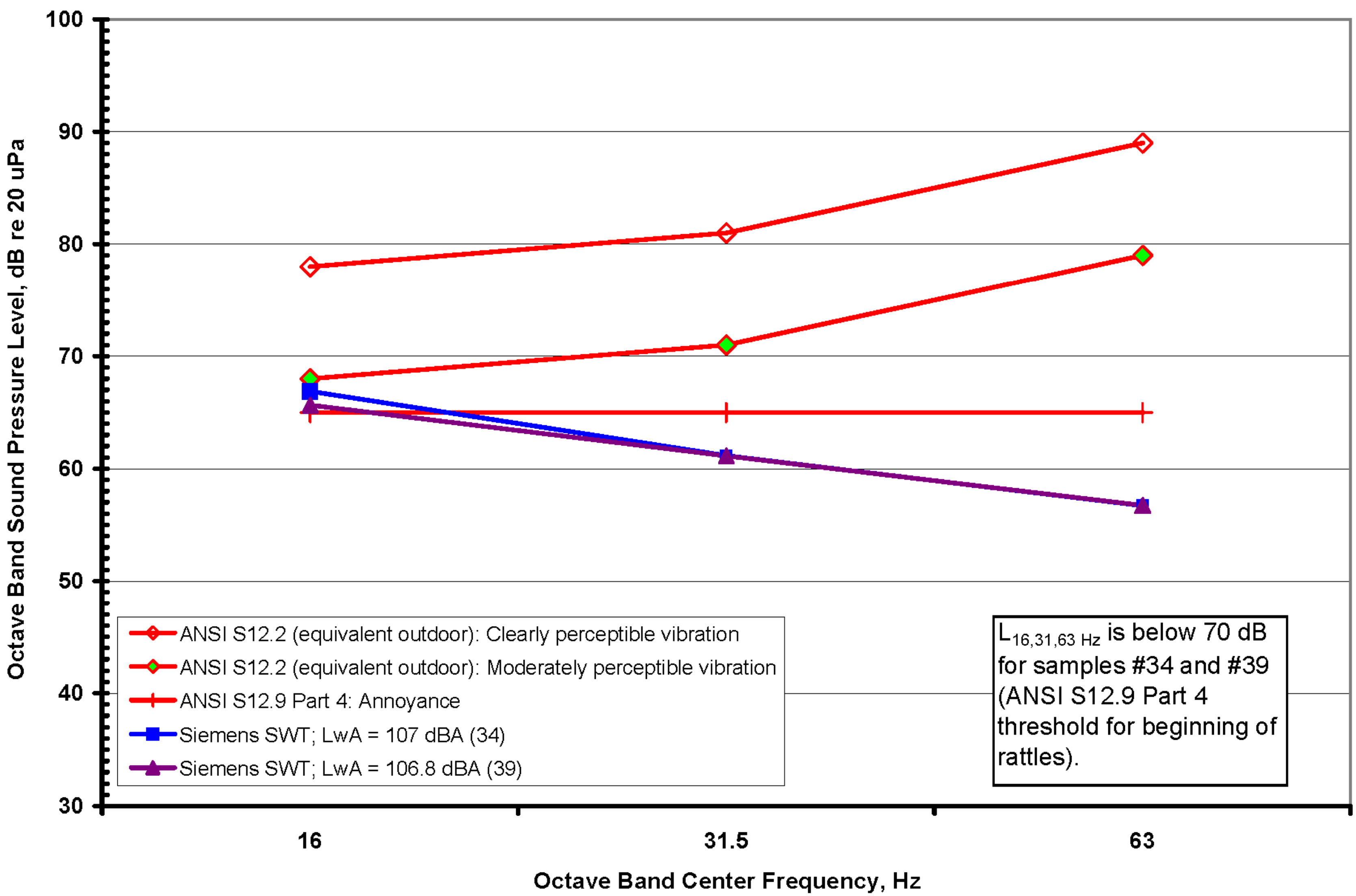


Figure 8.1-4a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to Audibility Criteria (Home "A")

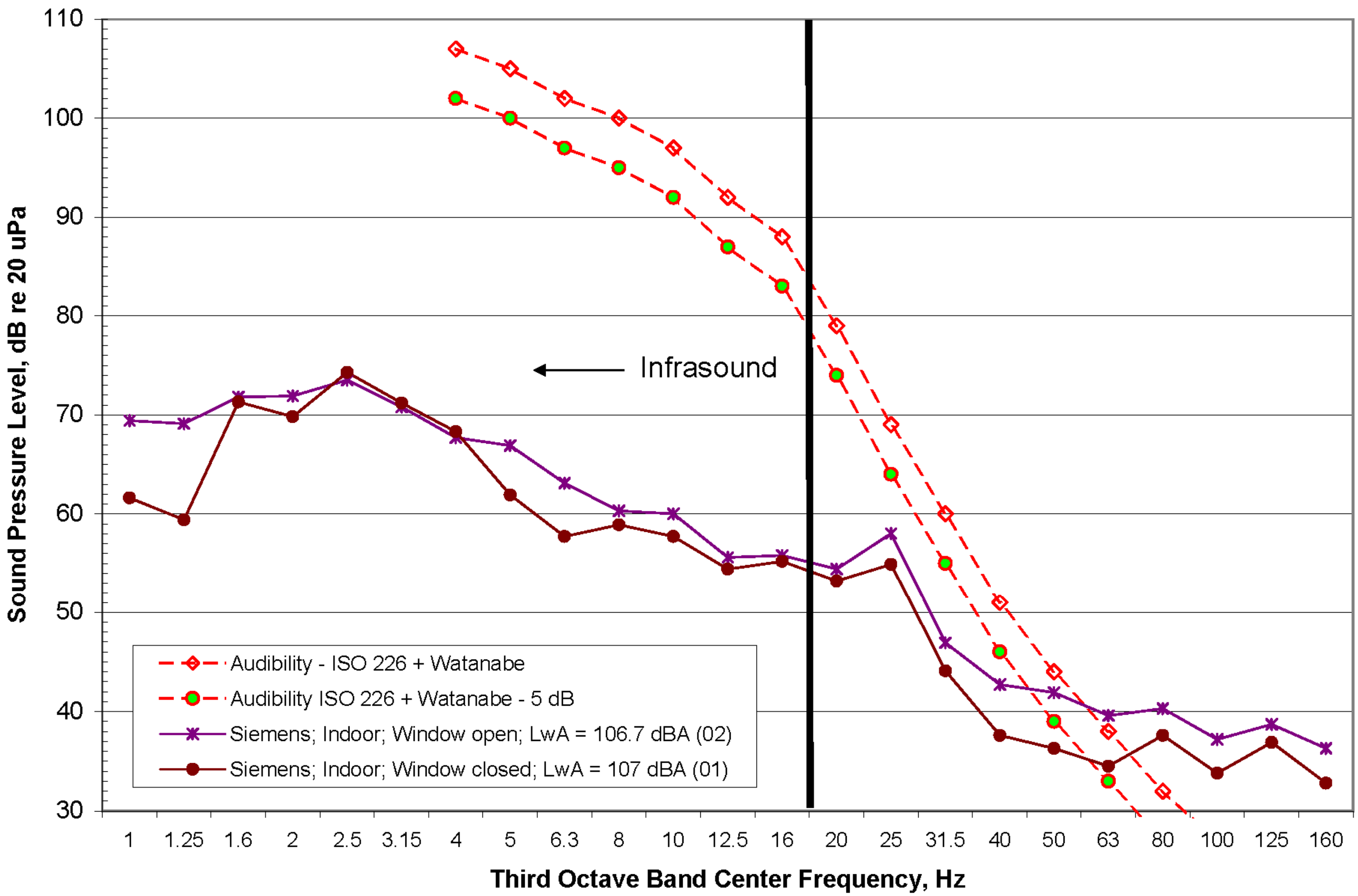


Figure 8.1-4b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to Audibility Criteria (Home "D")

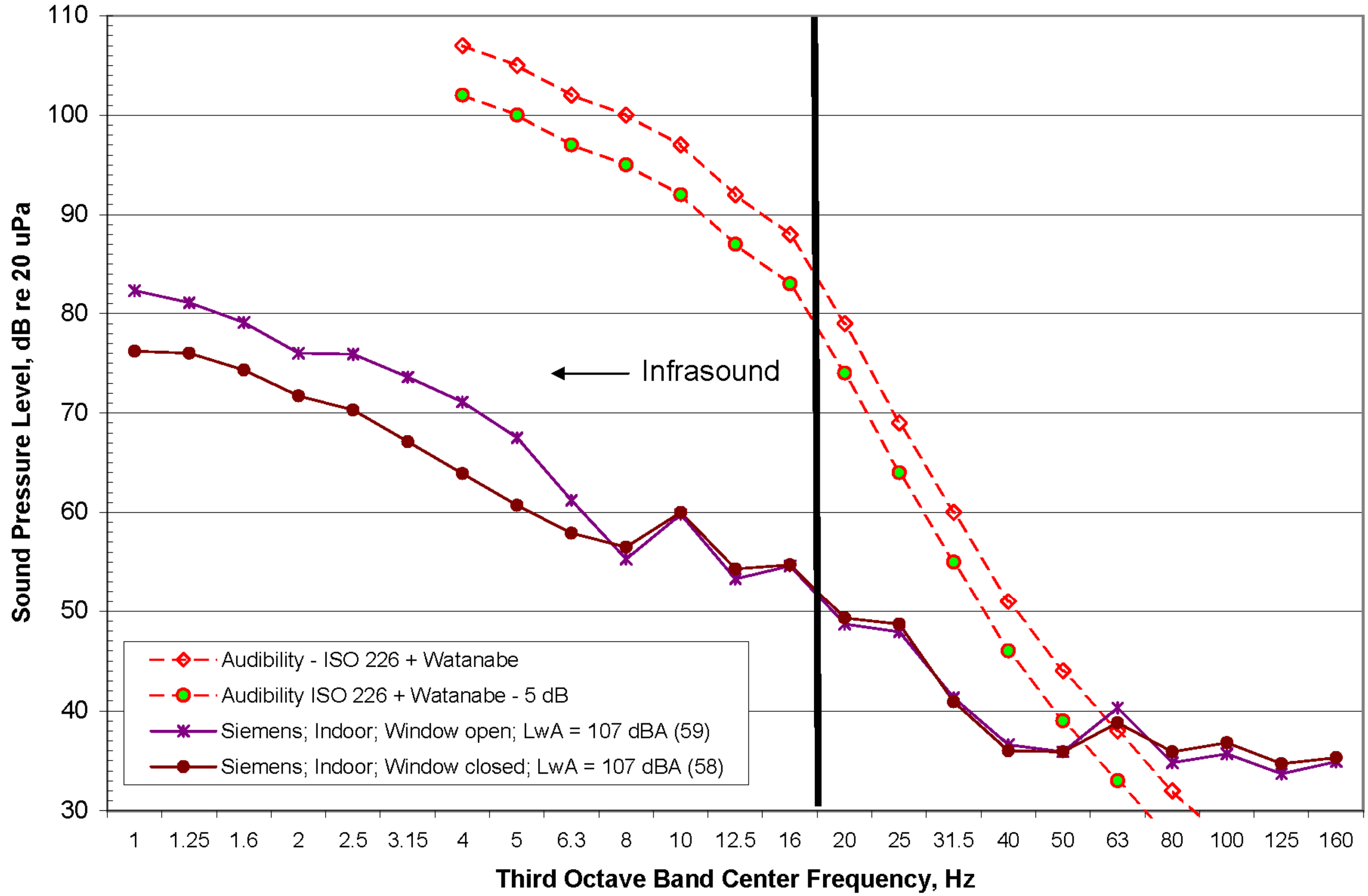


Figure 8.1-5a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to DEFRA Criteria (Home "A")

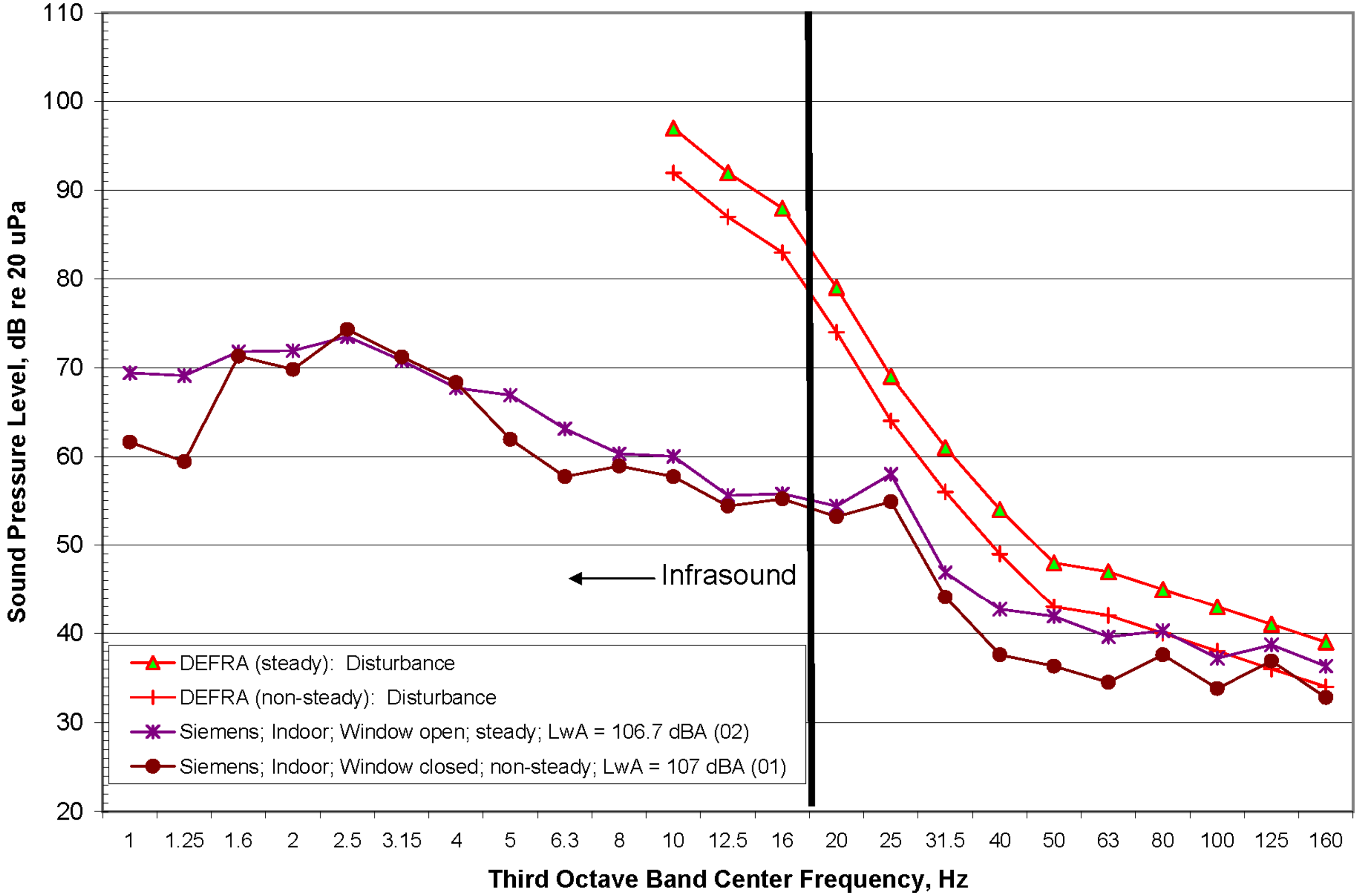


Figure 8.1-5b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to DEFRA Criteria (Home "D")

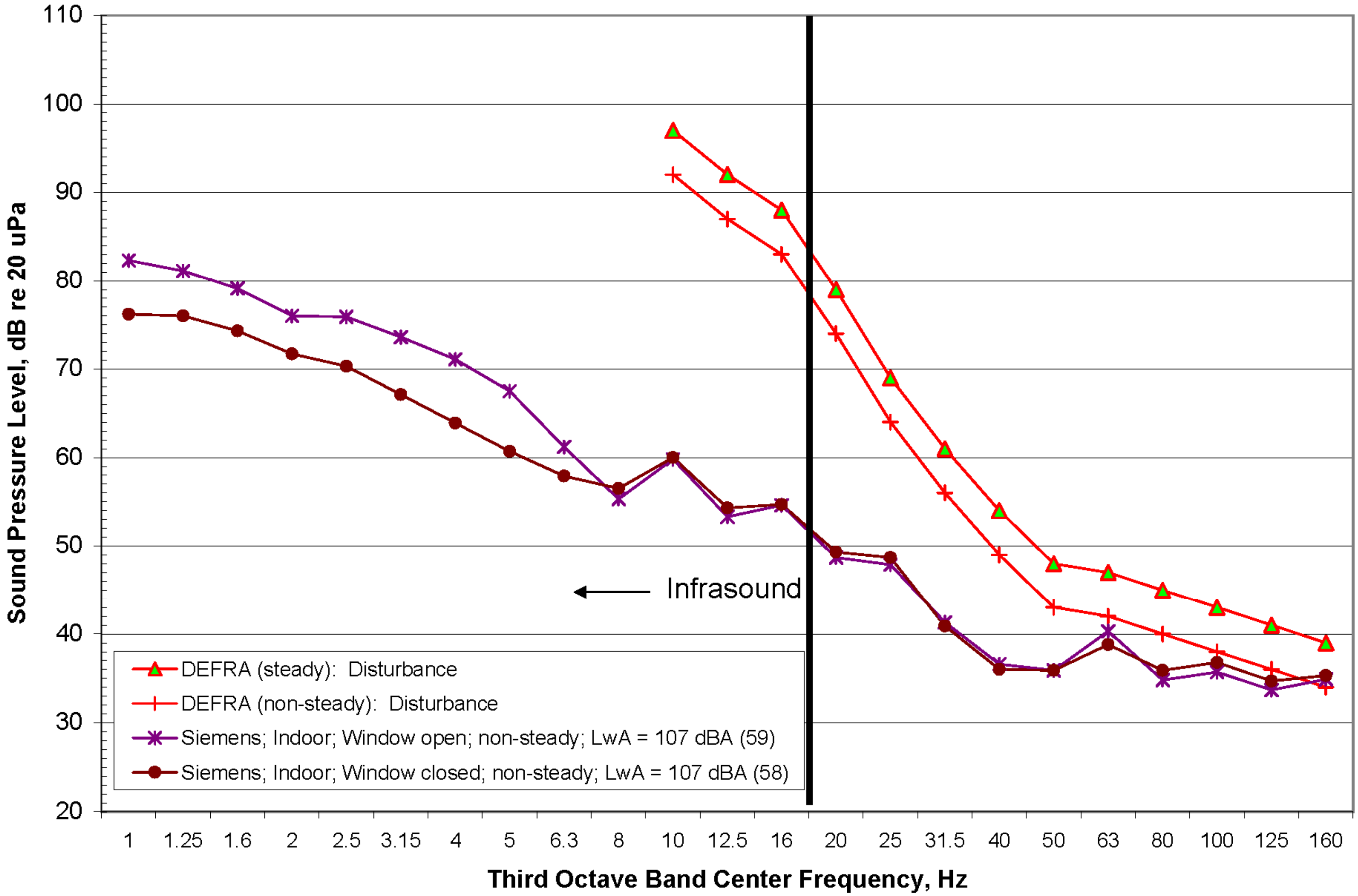


Figure 8.1-6a Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 1060 feet compared to ANSI 12.2 Criteria (Home "A")

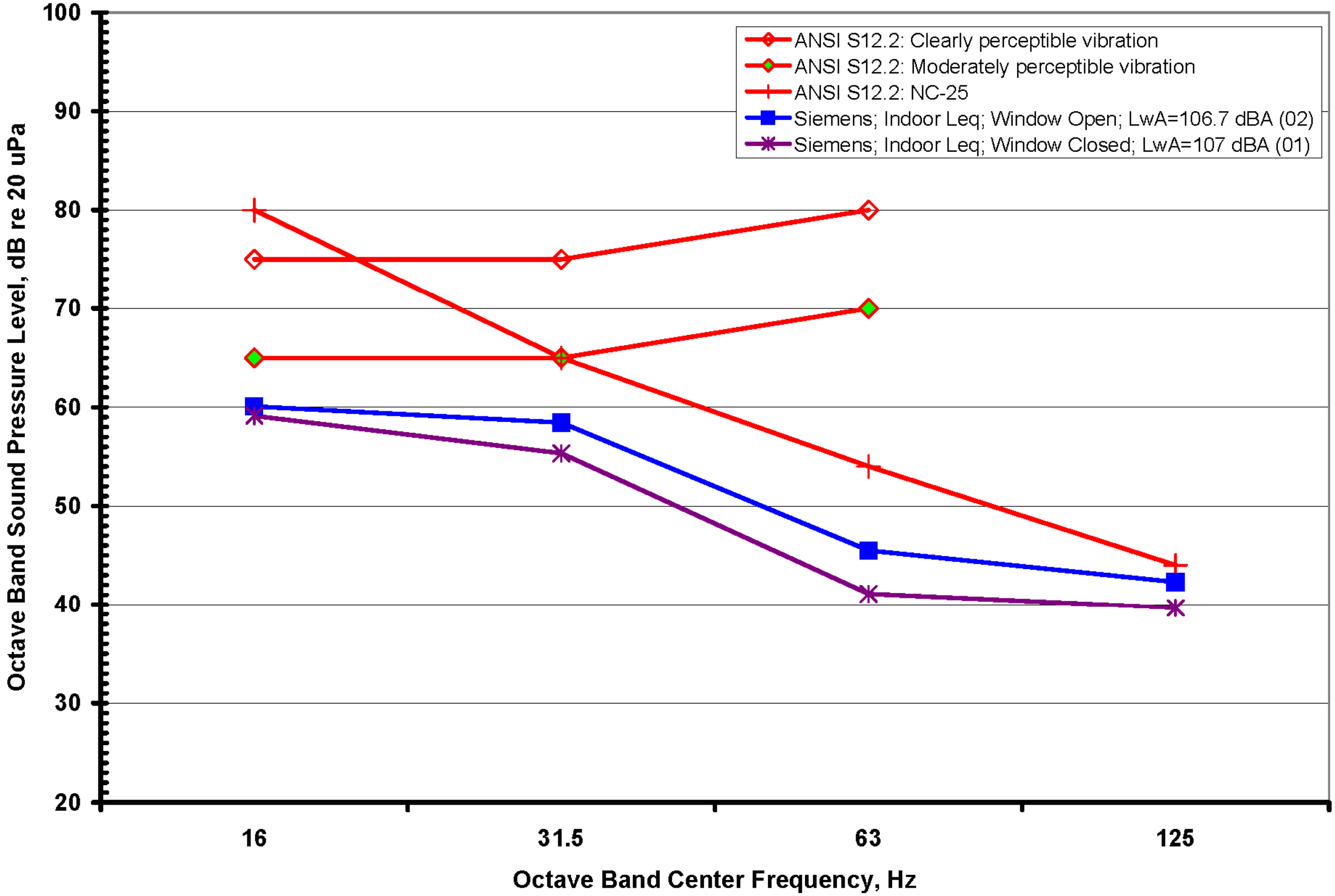


Figure 8.1-6b Siemens SWT-2.3-93 Wind Turbine Indoor Sound Levels at 920 feet compared to ANSI 12.2 Criteria (Home "D")

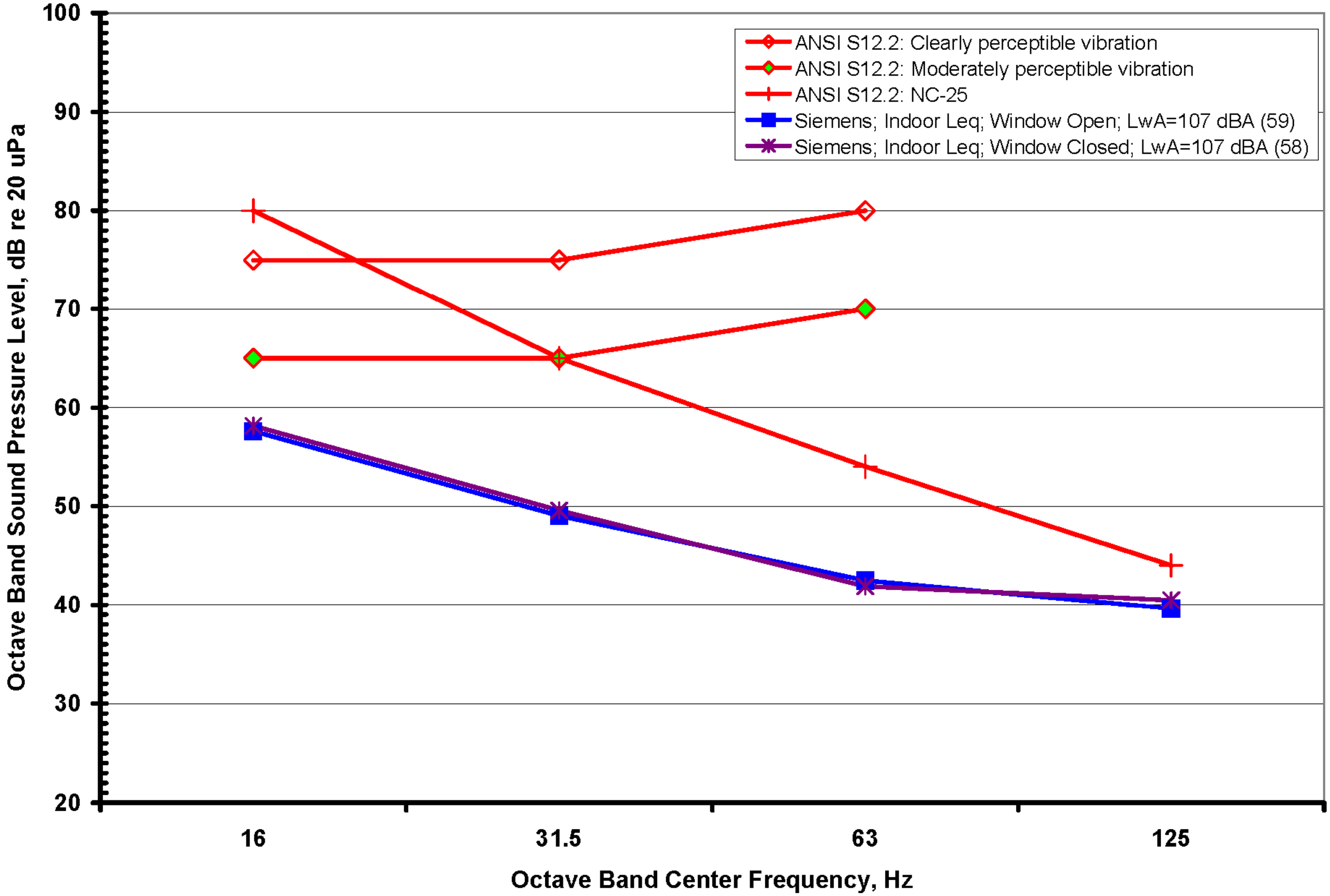


Figure 8.2-1 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to Audibility Criteria

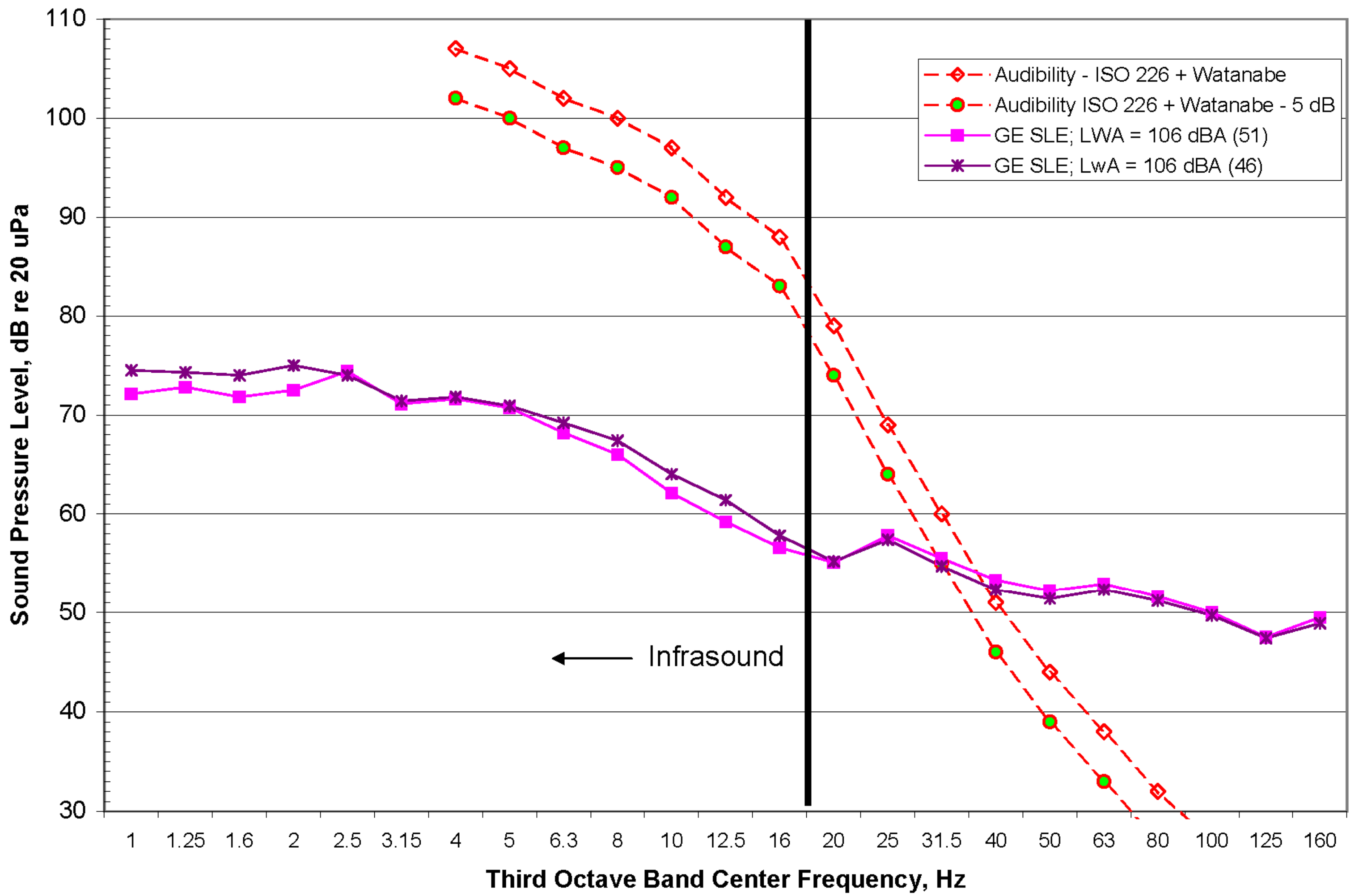


Figure 8.2-2 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to outdoor equivalent DEFRA Criteria

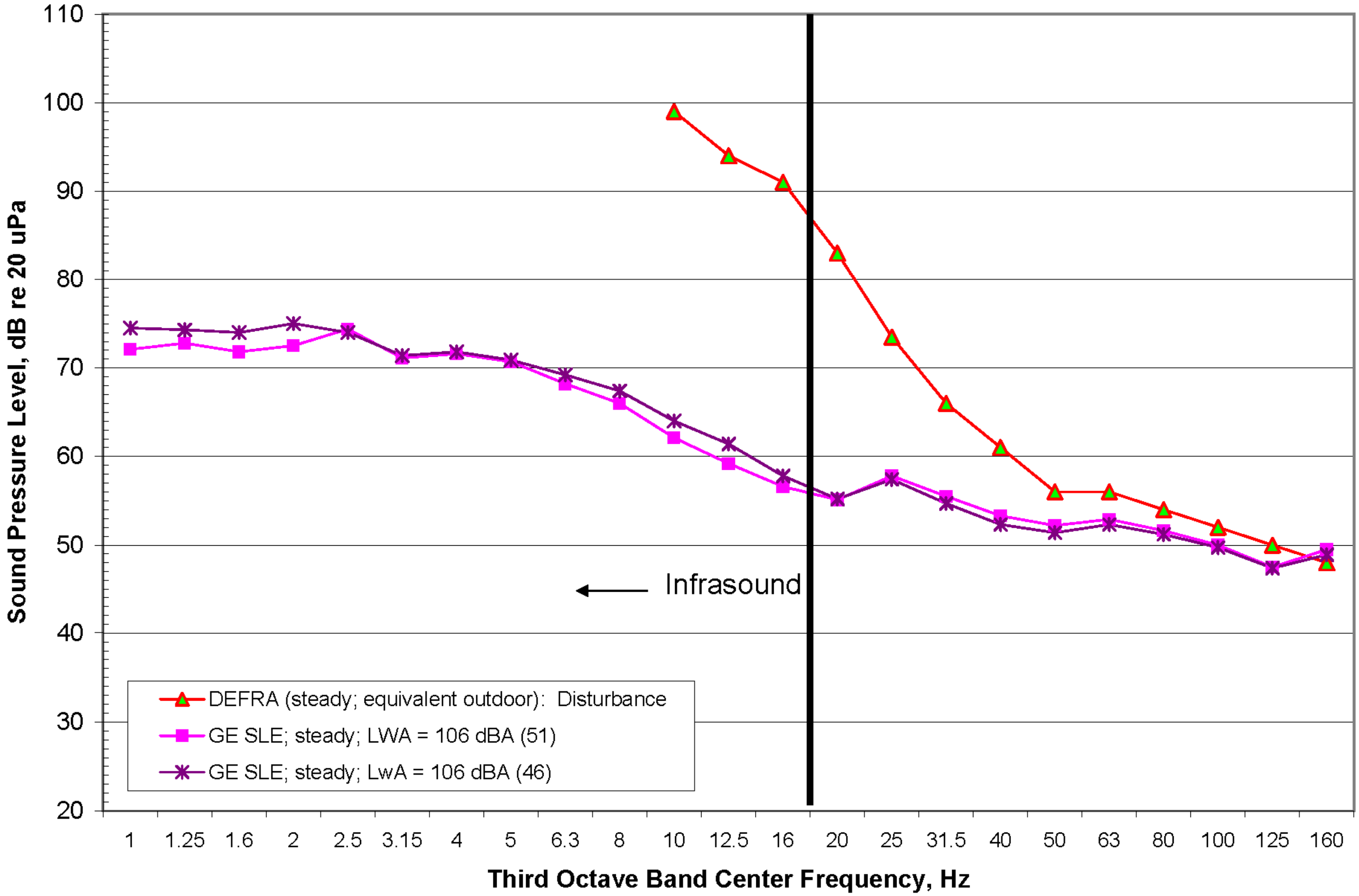


Figure 8.2-3 GE 1.5sle Wind Turbine Outdoor Sound Levels at 1000 feet compared to ANSI Criteria

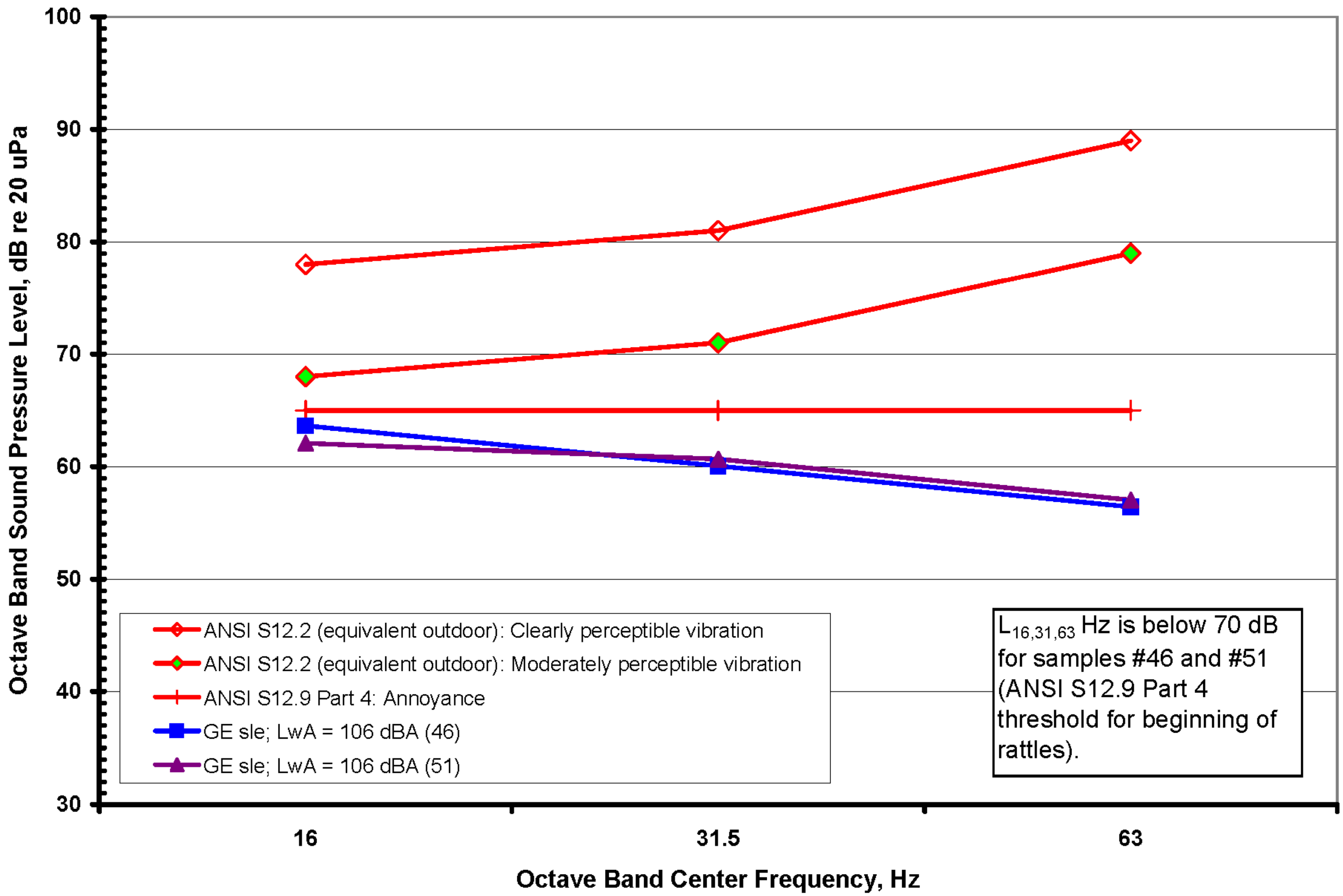


Figure 8.2-4a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to Audibility Criteria (Home "B")

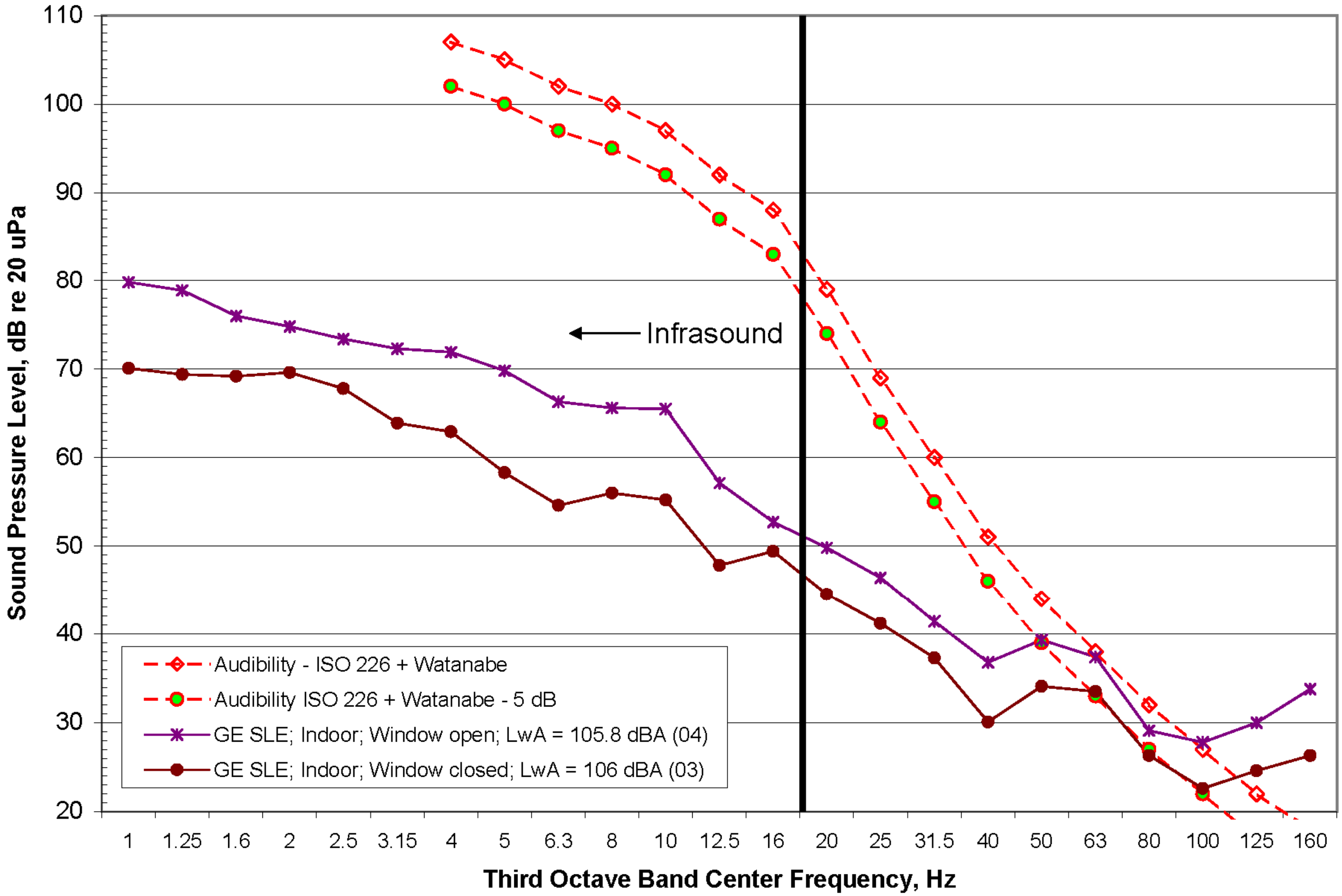


Figure 8.2-4b GE 1.5sle Wind Turbine Indoor Sound Levels at 1025 feet compared to Audibility Criteria (Home "C")

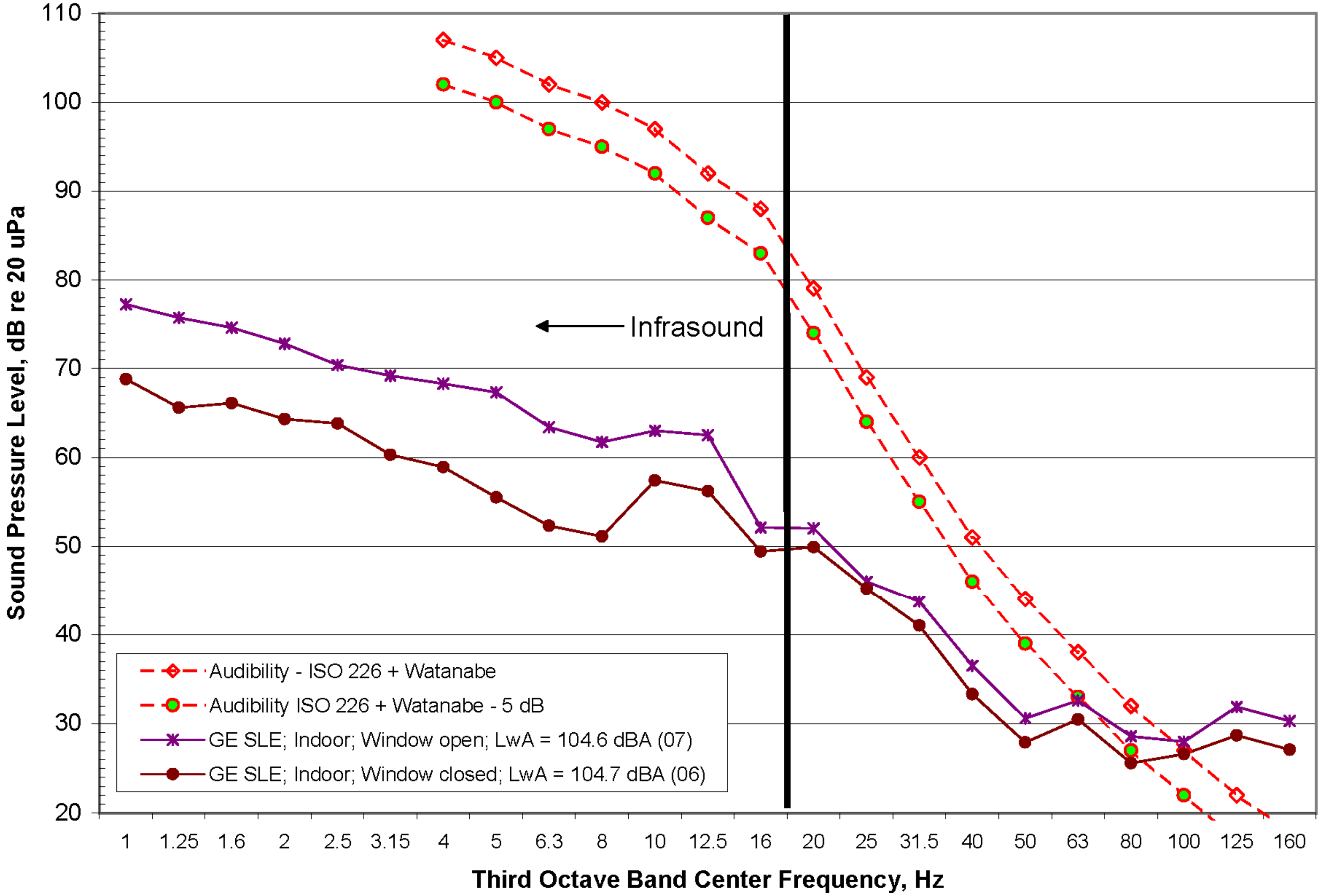


Figure 8.2-5a GE 1.5sle Wind Turbine Indoor Sound Levels at 950 feet compared to DEFRA Criteria (Home "B")

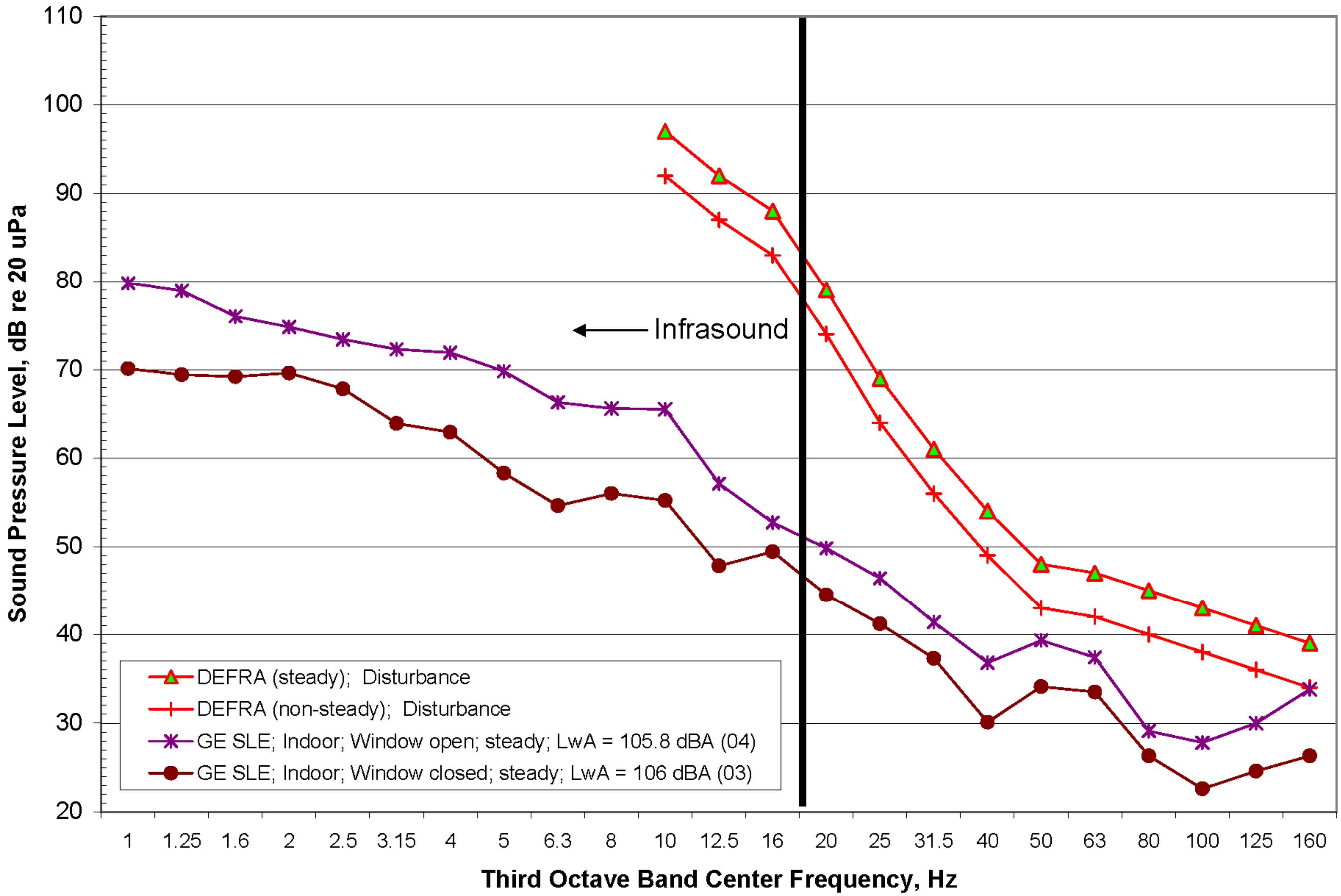


Figure 8.2-5b GE 1.5sle Wind Turbine Indoor Sound Levels at 1025 feet compared to DEFRA Criteria (Home "C")

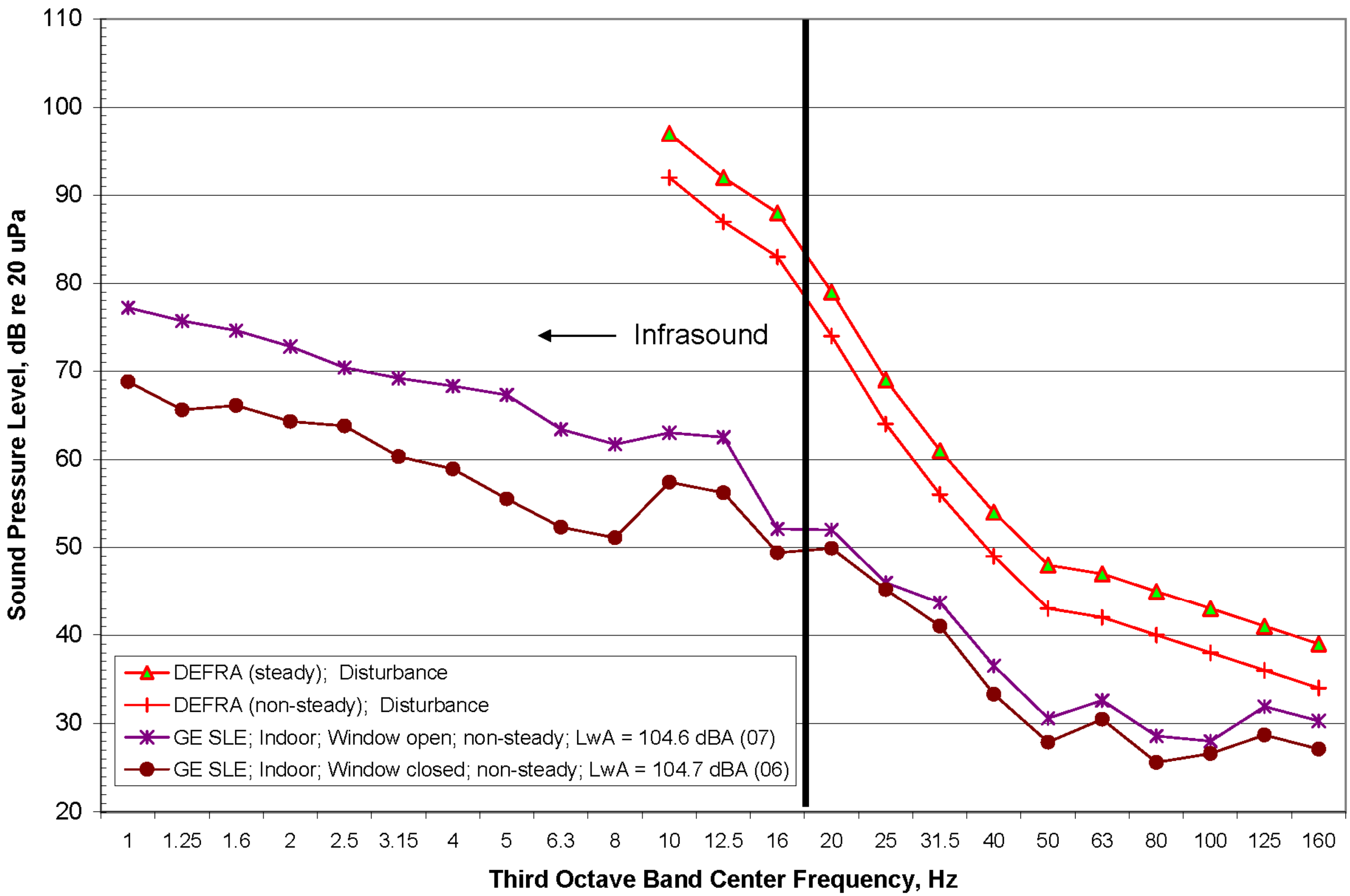


Figure 8.2-6a GE 1.5 sle Wind Turbine Indoor Sound Levels at 950 feet compared to ANSI 12.2 Criteria (Home "B")

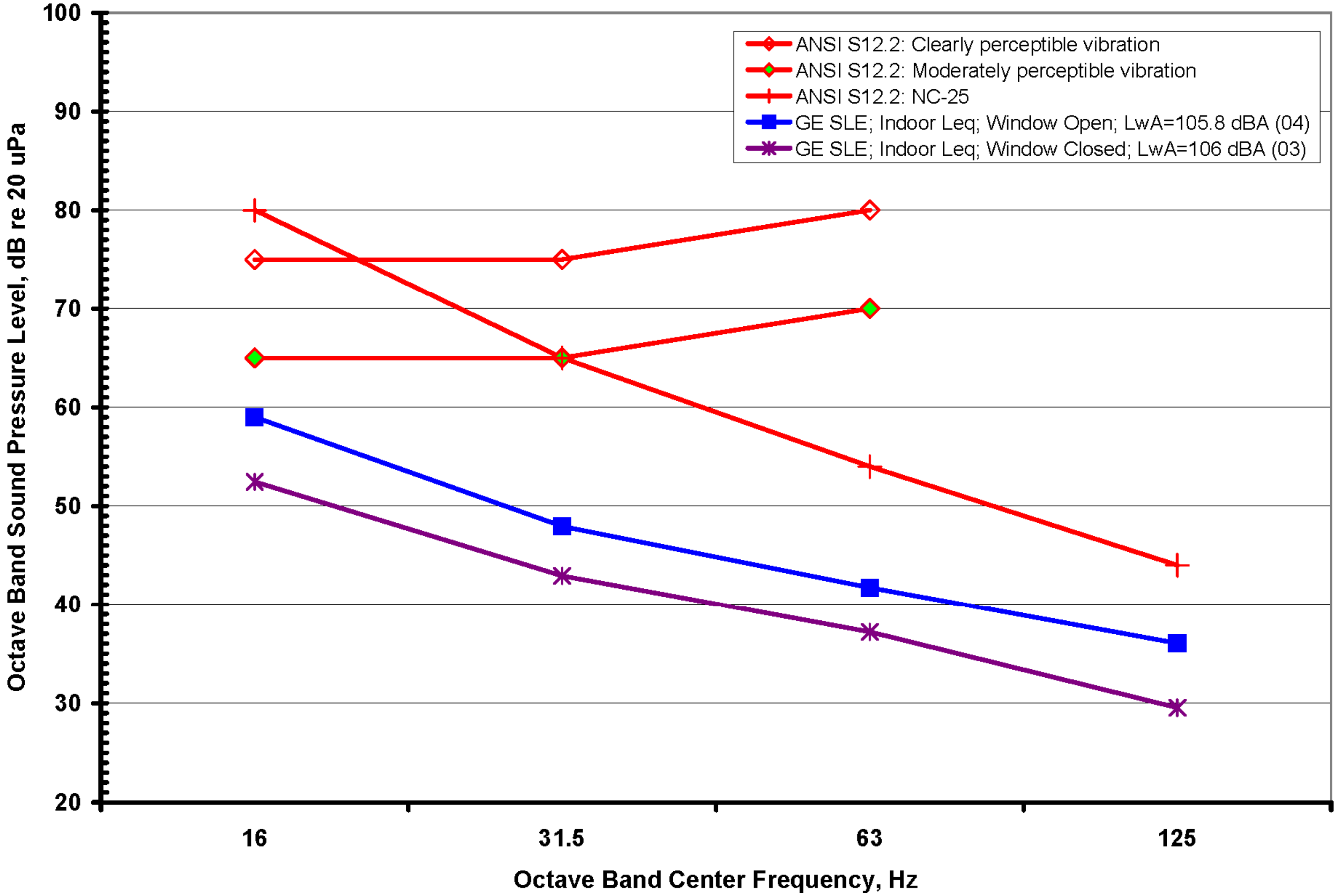


Figure 8.2-6b GE 1.5 sle Wind Turbine Indoor Sound Levels at 1025 feet compared to ANSI 12.2 Criteria (Home "C")

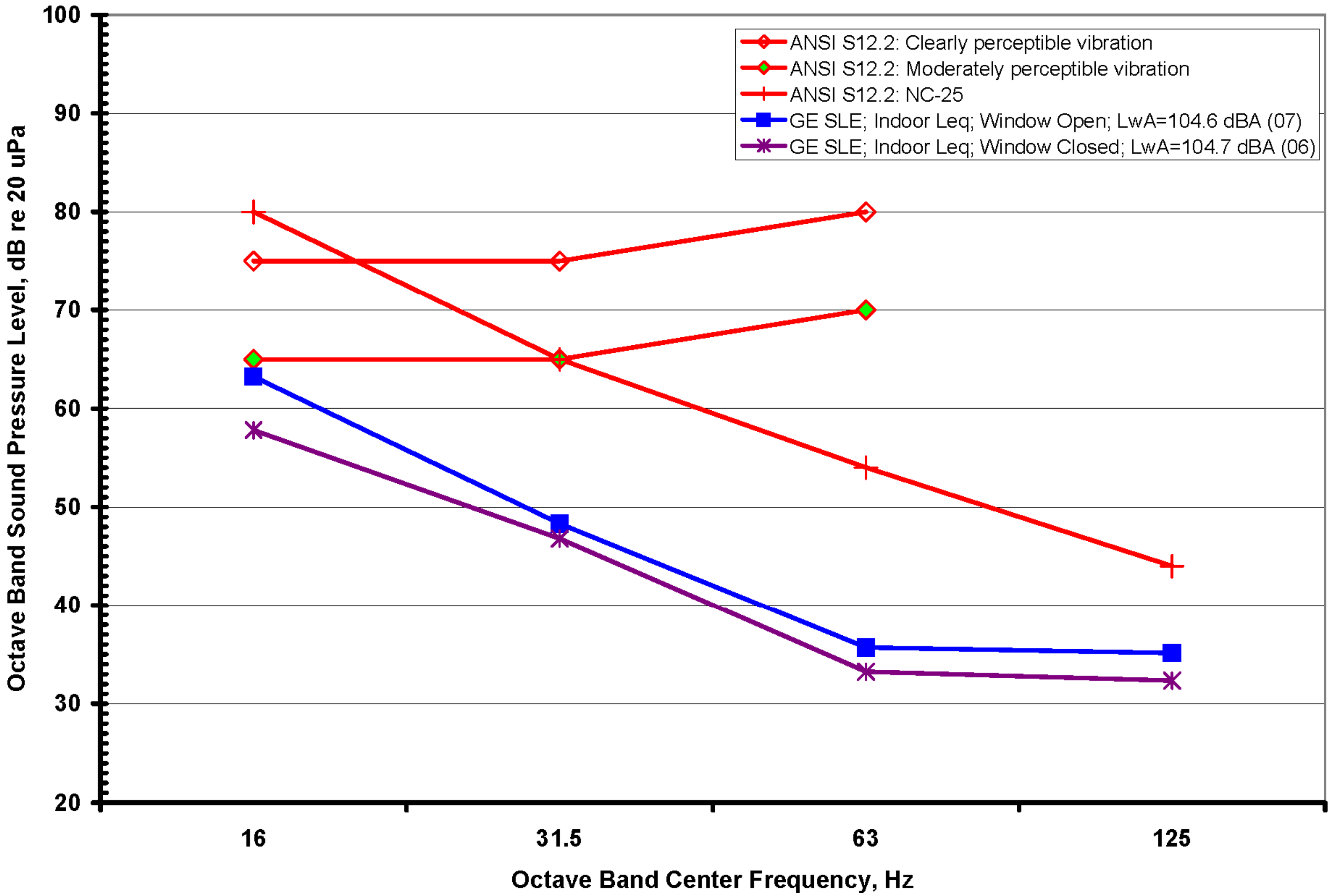


Figure 8.3-1a One-Third Octave Band Interior Noise Reduction – Windows Closed

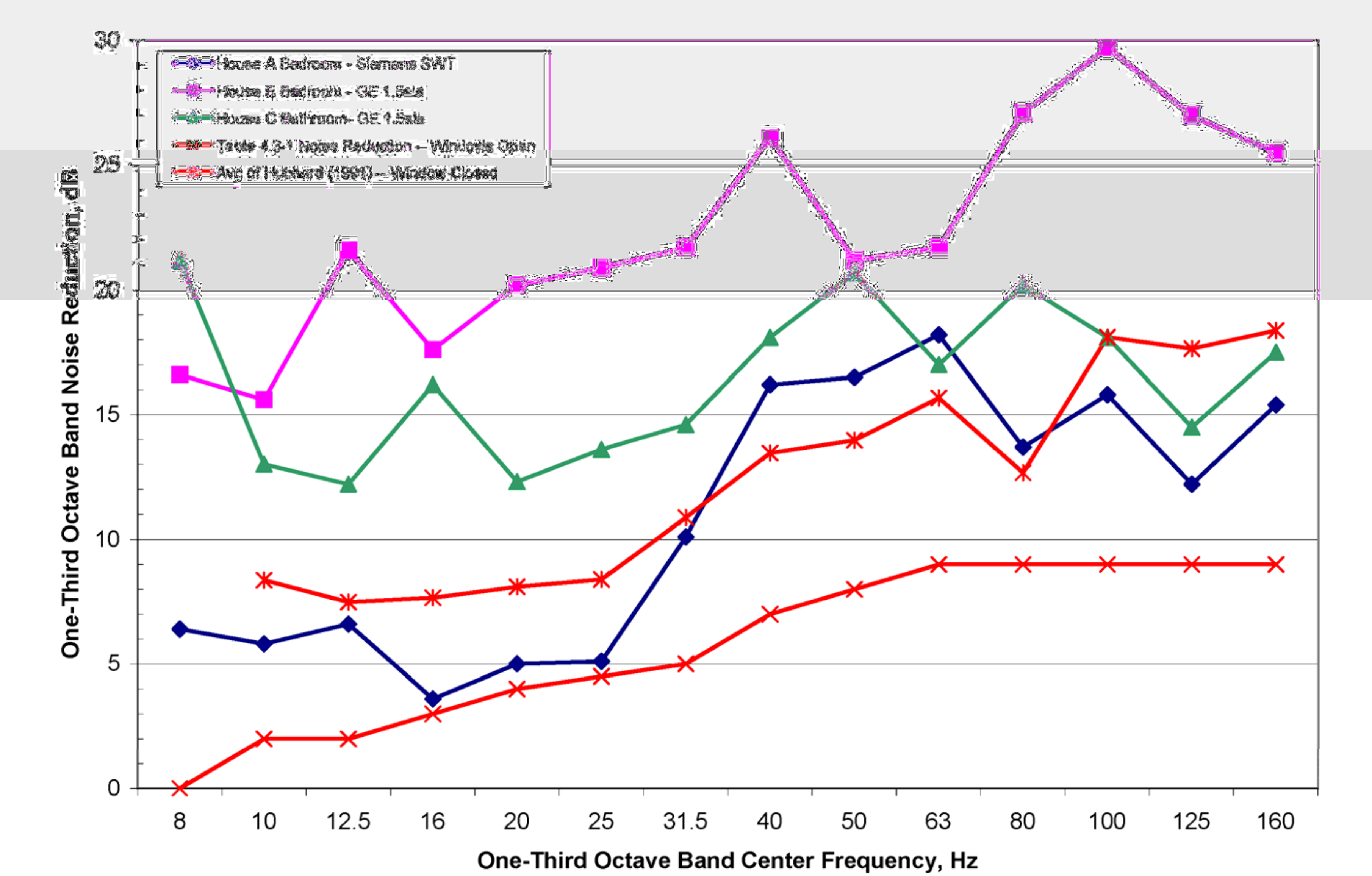
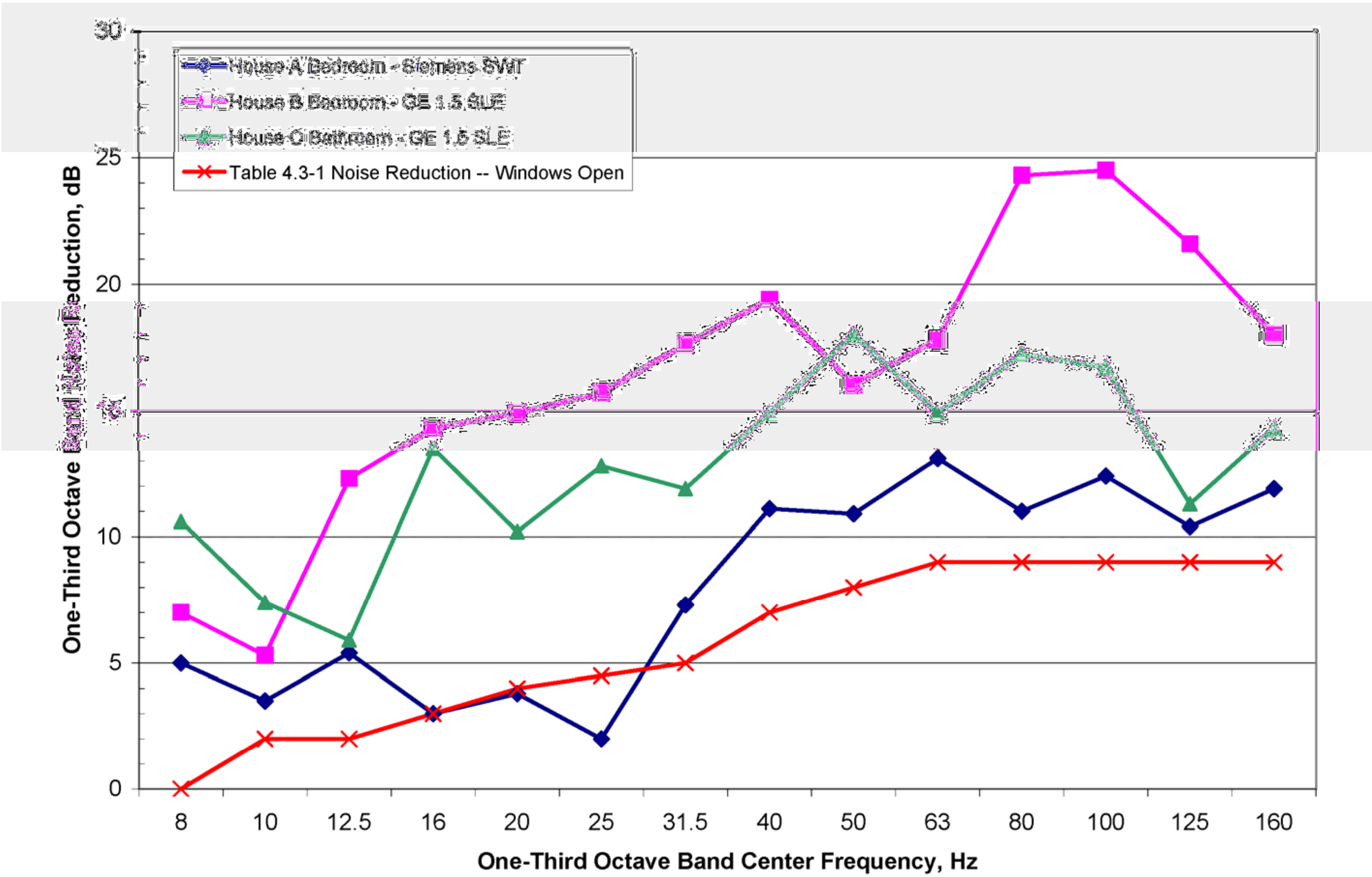


Figure 8.3-1b One-Third Octave Band Interior Noise Reduction – Windows Open



9.0 CONCLUSION

Siemens SWT 2.93-93 and GE 1.5sle wind turbines at maximum noise at a distance more than 1000 feet from the nearest residence do not pose a low frequency noise or infrasound problem. At this distance the wind farms:

- meet ANSI/ASA S12.2 indoor levels for low frequency sound for bedrooms, classrooms and hospitals;
- meet ANSI/ASA S12.2 indoor levels for moderately perceptible vibrations in light-weight walls and ceilings;
- meet ANSI S12.9 Part 4 thresholds for annoyance and beginning of rattles;
- meet UK DEFRA disturbance based guidelines;
- have no audible infrasound to the most sensitive listeners;
- might have slightly audible low frequency noise at frequencies at 50 Hz and above depending on other sources of low frequency noises in homes, such as refrigerators or external traffic or airplanes; and
- meet ANSI S2.71 recommendations for perceptible vibration in residences during night time hours.

In accordance with the above findings, and in conjunction with our extensive literature search of scientific papers and reports, there should be no adverse public health effects from infrasound or low frequency noise at distances greater than 1000 feet from the wind turbine types measured by Epsilon: GE 1.5sle and Siemens SWT 2.3-93.

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HEALTH & FAMILY SERVICES
PUBLIC HEALTH SERVICES
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June 1, 2009

His Worship Mayor Randy Hope and Councillors
The Municipality of Chatham-Kent
315 King Street West
Chatham, ON N7M 5K8

Dear Mayor and Councillors:

RE: REQUEST FOR FURTHER CLARIFICATION ON HEALTH EFFECTS OF WIND TURBINES

I am aware that Council has received a great deal of conflicting information on this issue, including health complaints in our own Municipality alleged to be caused by proximity to wind turbines. I will explain the position of the Health Unit that there is currently no substantial basis to conclude that wind turbines are directly eroding the health of people.

Evidence for medical conclusions is categorized into three levels, with level I providing the strongest evidence and level III the weakest.

- Level I: Evidence obtained from at least one properly designed randomized controlled trial.
- Level II-1: Evidence obtained from well-designed controlled trials without randomization.
- Level II-2: Evidence obtained from well-designed cohort or case-control analytic studies, preferably from more than one center or research group.
- Level II-3: Evidence obtained from multiple time series with or without the intervention. Dramatic results in uncontrolled trials might also be regarded as this type of evidence.
- Level III: Opinions of respected authorities, based on clinical experience, descriptive studies, or reports of expert committees.

Unfortunately, statistical analysis is limited with regard to wind turbine effects because of the paucity of level I and II evidence. Most of the so-called studies purporting to document adverse health effects caused by wind turbines are self-reported accounts or open surveys of health issues that are nonspecific and common irrespective of wind turbine exposure, such as insomnia, hypertension, anxiety, digestive disturbances and subjective sensory changes. These accounts have been reported by the media and have created an impression in the public before a rigorous analysis has confirmed that there is either excess morbidity or an association with wind turbines. Uncontrolled self-reporting eliminates any chance of scientific analysis as there is no motivation or reason to report a lack of symptoms or a way to include all people in proximity to turbines. There is no mechanism to exclude people from participating in a self-reported survey multiple times. The boundaries of proximity are often not even defined. The lack of controls (a sample of people not exposed to wind turbines), failing to blind the surveyors (they should not know the exposure history before asking the questions) and not defining the study population result in what researchers call preselection bias. Similar surveys in the past have tended to distort and overestimate the prevalence of many things from “cancer clusters” to sexual practices (Kinsey’s infamous sex surveys). There is no local data on the prevalence of these symptoms before wind turbines were installed, so it cannot be determined whether or not there has been an increase. The most eloquent spokesman for the anti-wind turbine activists, former UWO Dean of Medicine Dr Robert McMurtry, has admitted that there are no controlled studies, and he has called on the province to conduct such a study. This has been supported by at least one Ontario Health Unit, but this would be methodologically difficult. It is not possible to design a study to conclusively prove a lack of association, such as that wind turbines cannot cause health effects or that there are no ghosts.

At the present time we have people who have concluded, with gut-felt certainty, that they have health problems caused by wind turbines. These reports have received a great deal of media attention and organized political action groups have been formed which advocate for government action to address these health problems and suspend the construction of wind farms. These objectors operate web sites and write letters which promulgate dubious explanations such as infrasound induced DNA alterations, “wind turbine syndrome”, coined by anti-wind turbine activist Dr Nina Pierpont of Malone, New York for a complex of nonspecific symptoms and “vibro-acoustic disease”, tissue fibrosis first ascribed to extreme sound and vibration exposure in aviation environments by Portuguese investigators Alves Pereira and Castelo Branco, but later associated with the much lower sound levels of wind turbines and even automobiles. No other researchers have confirmed these findings. Wind turbine syndrome and vibro-acoustic disease impress lay persons as legitimate diseases which account for how they are feeling, but neither is listed in the International Classification of Diseases nor is described in any standard medical textbook. Most experts are skeptical that they exist.

So can we make sense of these complaints?

Most health complaints regarding wind turbines have centered on sound as the cause. Three kinds of sound are emitted by wind turbines: infrasound (oscillation frequencies less than approximately 10 Hz), low frequency sound of approximately 10-200 Hz and the fluctuating aerodynamic “swish” from the turbine blades which is also low frequency, approximately 500-1000 Hz.

Infrasound from natural sources (meteors, volcanic eruptions, ocean waves and wind) surrounds us and is below the audible threshold. The infrasound emitted from wind turbines is at a level of 50 to 70 dB, also well below the audible threshold. There is a consensus among acoustic experts that the infrasound from wind turbines is of no consequence whatsoever. A problem is that objectors often use the term infrasound incorrectly when they are referring to low frequency sounds.

Low frequency sounds below 40 Hz cannot be distinguished from background noise due to the wind itself. Perceptible (meaning above the background noise) low frequency noise can be produced by wind turbines under conditions of unusually turbulent wind conditions, but the actual sound level depends on the distance of the listener from the turbine, as the sound attenuates (falls off). The higher the frequency and the higher the temperature, the greater the sound attenuates with distance. Terrain and humidity are other factors. The low frequency noise emitted by spinning wind turbines could possibly be annoying to some when winds are unusually turbulent, but there is no evidence that this level of noise could be harmful to health. If so, city dwelling would be impossible due to the similar levels of ambient noise levels normally present in urban environments. It is not usually the low frequency nonfluctuating noise component that provokes complaints.

The fluctuating aerodynamic sound (swish) in the 500-1000 Hz range is from the wind turbine blades disturbing the air, modulated by the blades passing the tower which changes the sound dispersion characteristics in an audible manner. This fluctuating aerodynamic noise is the cause of most noise complaints regarding wind turbines, as it is harder to become accustomed to fluctuating noise than to noise that does not fluctuate. The noise limits imposed by the Ministry of the Environment for wind turbines are designed to prevent noise issues but some wind turbines produce noise levels that may be irritating and even stressful to some people who are more sensitive to noise. Sleep disturbance can occur. Others exposed to the same noise levels may experience no difficulty. There is no evidence of direct effects to health by this level of noise but there could be indirect effects from annoyance-induced stress. One paper categorically states that the only health effect of wind turbine noise is annoyance.[1]

There is a large body of medical literature on stress and psychoacoustics. There is a great deal of individual variation in the response to any given stimulus and legislated limits to noise and other annoyance factors are not designed to prevent problems in the most sensitive members of the population. Three factors that seem particularly

[1] Regan B., Casey T.G. Wind Turbine Noise Primer, Canadian Acoustics Special Issue, 34 (2) June 2006

pertinent to the discussion of wind turbine effects are the fear factor, also called the nocebo effect, and two medical conditions, sensory integration dysfunction and somatoform disorders.

The large volume of media coverage devoted to the alleged adverse health effects of wind turbines understandably creates an anticipatory fear in some that they will also experience adverse effects from wind turbines. Every person is suggestible to some degree. The resulting stress, fear and hypervigilance may exacerbate or even create problems which would not otherwise exist. In this way, anti-wind farm activists may be creating with their publicity some of the problems which they describe. This is the nocebo effect and it is the negative counterpart to the placebo effect where belief in an intervention may produce positive results.

Sensory integration dysfunction is a little-understood condition of abnormal sensitivity to any or all sensory stimuli (sound, touch, light, smell, taste). The afflicted experience unpleasant overpowering sensations to ambient conditions considered normal by most people. There is little data on the prevalence of this condition and it may be more common than is realized. Such individuals would be more sensitive to wind turbine noise than most.

Somatoform disorders are characterized by physical symptoms which reflect psychological states rather than physical causes. Conversion is the unconscious expression of stress and anxiety as a physical symptom and it is very common. Common conversion symptoms are vague sensations of tingling or discomfort, fatigue, poorly localized abdominal pain, headaches, back or neck pain, weakness, loss of balance, hearing and visual abnormalities. The wind turbine controversy has raised the rhetoric to stressful levels, and the similarities of human stress responses and conversion symptoms to those described as so-called wind turbine syndrome are striking.

In summary, there is no scientifically valid evidence that wind turbines are causing direct health effects, although the body of valid evidence is limited. It is unlikely that evidence of adverse health effects will emerge in the future because there is no biologically plausible mechanism known by which wind turbines could cause health effects. There are wind turbines in urban environments, including Toronto, that have not been causing problems. The European experience would indicate that wind farms can be compatible with rural environments. An annoyance factor undoubtedly exists to which there is individual variability. Associated stress from annoyance, exacerbated by all the negative publicity, is the likely cause for the purported erosion of health that some people living near rural wind turbines are reporting. Stress has multiple causes and is additive.

Unfortunately, there has been some misunderstanding regarding the role of the Medical Officer of Health and the Health Unit in these matters. It is beyond the scope of the

Chatham-Kent Health Unit to address this in any but a general manner. In my opinion the issue of wind turbine noise and associated stress needs to be managed at the Provincial level. If the Ministry of the Environment noise guidelines for wind turbine installations are exceeded, affected people have the option to pursue compensation, but the Chatham-Kent Board of Health has confirmed that it is not the role of the Health Unit to become involved in private litigation matters. From the outset, when requested by Council, the Health Unit and I have attempted to provide a balanced, evidence-based and scientifically valid appraisal of this whole situation to Council. As a result, anti-wind farm activists have attacked me personally on internet sites, accused me of being financially influenced by wind turbine manufacturers (untrue) and even made complaints about my conduct to regulatory bodies. Letters to the Chatham Daily News have castigated me for neglecting the health of Chatham-Kent citizens with the kind of inflammatory phrases spoken, it seems to me, in the language of people with a higher regard for their own convictions than for the facts.

Sincerely,

W. David Colby, MSc, MD, FRCPC
Acting Medical Officer of Health
Chatham-Kent Health Unit

Encl.:

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ACOUSTIC CONSULTING REPORT
Prepared for the Ontario Ministry of the Environment

WIND TURBINE FACILITIES NOISE ISSUES

Aiolos Report Number: 4071/2180/AR155Rev3
DECEMBER 2007

Author Ramani Ramakrishnan, Ph. D., P. Eng.
Lead Acoustician

Signature
Date: 28 December 2007

AIOLOS ENGINEERING CORPORATION

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EXECUTIVE SUMMARY

All proponents of a wind farm development need to apply for a Certificate of Approval from the Ministry of the Environment of Ontario. The noise assessment report required for the approval process uses the guideline Ministry document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" released in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits.

The Ministry has now initiated a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry's approach to regulating noise impacts of wind turbines.

The scope and requirements of the review can be summarized as: a) Review of the 2006 doctoral dissertation by van den Berg; b) Review of available noise policies and guidelines; review of relevant scientific literature; and review of MOE's current noise policies as applied to wind turbine noise and c) Provide expert opinion based on the above findings; and d) Prepare a report that provides advice on the state of the science regarding wind turbine noise, and on MOE policies and procedures that relate to wind turbine facilities. The results of the investigations are described below.

Van den Berg's research was initiated as a result of complaints, in Netherlands, against an existing wind farm in Germany very close to the Dutch border. The main hypotheses of the research are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds can become very pronounced during stable and very stable conditions. Although, the data of van den Berg's research did not provide conclusive scientific evidence to support the above hypotheses, further review of the literature showed that some of the basic conjectures may well be true. Hence, the research of van den Berg must be considered as the catalyst that started serious discussion on many noise aspects of wind farm. Future research must therefore provide strong scientific data to validate these different noise concerns.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. General comparison of the noise regulations was presented. The main differences between the different regulations seem to be: i) in the acceptable noise limits; and ii) in the evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm. Further, some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. The Ministry of the Environment assessment process in Ontario is similar to other jurisdictions.

A literature review, focussed mainly on a) Metrological effects on wind turbine noise generation; b) Assessment procedures of wind turbine noise levels and their impact; c) Particular characteristics of wind farm noise; and d) Human responses to wind farm noise levels, was conducted. It showed that - local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines; assessment procedures of sound power levels and propagation models, applied in different jurisdictions are quite similar in their scope; wind farm noise do not have significant low-frequency (infrasound) components; and modulations effects can impact annoyance;

The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.

1.0 INTRODUCTION

1.1 BACKGROUND

The Ministry of the Environment released a guideline document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. The revisions to NPC-205/NPC-232 (in draft form) did not change the evaluation of noise limits and/or procedures applicable to wind turbines. The three Ministry documents are enclosed in Appendices A through C.

The Ministry has now decided to initiate a review of the interpretation of the above policies, due to expanding body of knowledge of the noise impacts of wind turbines. The main aim of the proposed review is to assess the appropriateness of the Ministry's approach to regulating noise impacts of wind turbines. And the Ministry, to support the proposed review, has retained Aiolos Engineering to provide acoustical technical expert advice on the recent findings about low frequency and wind profiles on wind turbine noise impacts.

The scope and requirements of the technical advice can be summarized as shown below:

(1) *Review of the 2006 doctoral dissertation by van den Berg*;
(2) *Review of*
    2.1 available noise policies and guidelines;
    2.2 Review of relevant scientific literature; and
    2.3 Review of MOE's current noise policies as applied to wind turbine and
(3) *Provide expert opinion based on the above findings;*
(4) *Participate in a focus group discussion;* and
(5) *Prepare a report that provides advice on the state of the science regarding wind turbine noise and on MOE policies and procedures that relate to wind turbine facilities.*

2.0 REVIEW OF G. P. VAN DEN BERG'S DISSERTATION

2.1 BACKGROUND

Dr. G. P. van den Berg of the University of Groningen conducted research on the noise characteristics of wind turbines, the impact of wind profiles on its propagation as well as the subjective response of sensitive receptors. The results of the above research are summarized in the 2004 Journal of Sound and Vibration article (Reference 2) with the details given in his 2006 doctoral dissertation (Reference 1).

A list of documents used for this assessment is enclosed in the reference list. *NOTE:* References 2, 3 and 4 by van den Berg presents only summary results of his research and the complete details are included in his dissertation (Reference 1). Hence, references 2, 3 and 4 will not be commented upon in this review.

The main aims of van den Berg's dissertation can be summarized as follows:

i) A group of residents complained against the perceived noise effects from a wind farm located along the border between Germany and Netherlands and were unable to obtain satisfactory resolution from the authorities and hence the university's Science Shop for Physics was retained to investigate the validity of the residents' claims;

ii) The main complaints seem to centre around perception during evening and night hours, and hence the dissertation focussed on atmospheric stability and the resulting noise effects;

iii) The main hypotheses are: a) atmospheric stability, particularly stable and very stable conditions happen mostly at night time and the hub-height wind speeds can be higher than those predicted from the 10 m high wind speeds using standard methods, such as the logarithmic profiles of the IEC standard. And hence, the wind turbine noise levels can be higher than expected. It was also conjectured that these discrepancies are prevalent during summer months; and b) beat-sounds can become very pronounced during stable and very stable conditions.

The research uses a set of measurements near one wind farm as well as wind data from locations between 10 km and 40 km from the wind farm area. The whole thrust of the dissertation is to prove the hypotheses listed above.

The dissertation is broken into ten chapters, four general sections and four appendices. The chapter titles are: I) Wind power, society and this book: an introduction; II) Acoustical practice and sound research; III) Basic Facts; IV) Loud sound in weak winds; V) The beat is getting stronger; VI) Strong winds blow upon all turbines; VII) Thinking of solutions; VIII) Rumbling sound; IX) General conclusions and X) Epilogue.

Chapter I is basically an introduction and a justification for conducting the doctoral research by van den Berg. The reasons are seen to be based on anecdotal responses rather than from a truly scientific and statistical analysis of response surveys. Chapter II is a strong criticism of acoustic consultants and their inadequate effort in finding the true wind turbine noise levels and their potential impacts.

Chapters III, IV, V and VI are the relevant chapters for this review and assessment. The assessment will be presented in subsequent sections. Chapters VII through X are not critical for the current assessment and will not be commented upon. The assessments are presented next.

2.2 CHAPTER III – BASIC FACTS

Chapter 3 contains four sections and Sections 2 and 4 provide relevant background materials. Section 2 discusses wind profiles and Section 4 presents the many sources of wind turbine sound.

2.2.1 Wind Profiles and Atmospheric Stability

The main contention of this dissertation is that the hub-height velocity can be much higher than predicted with simple formula used currently in standards and other literature. This section presents two simple velocity profile equations to obtain wind velocities at different heights (Equations III.1 and III.3). Eq. III.3 is the standard logarithmic profile used in current literature.

This equation is being questioned as to its validity by this dissertation. Equation III.1 is a simple power law relationship with a shear coefficient as the exponent. Even though the dissertation states that Eq. III.1 has no physical basis, the dissertation applies this equation with 'suitably chosen' shear coefficient 'm' throughout the dissertation. Equation III.1 has been applied in many areas of engineering application and it is based both on dimensional analysis and empirical relationship obtained from field measurements. These two equations from Reference 1 are presented here for completeness sake.

$$V_{h2} / V_{h1} = (h_2/h_1)^m \qquad \text{III.1}$$

where 'm' is the shear coefficient, h_1 and h_2 are the two heights and V are the wind velocities at heights h_1 and h_2.

$$V_{h2\ log} / V_{h1} = \log(h_2/z_0) / \log(h_1/z_0) \qquad \text{III.3}$$

where z_0 is a roughness length of the surrounding terrain.

2.2.2 Main Sources of Wind Turbine Sound

A brief summary is presented of the different mechanism of noise generation including the interaction between the mast and the blade. Considerable amount of literature is available that outlines the noise from rotating aerofoil from early 1900s onwards. Hence, the information presented is a summary of earlier research.

However, it must be pointed that the dissertation mentions and/or presents information throughout the dissertation either heuristically or by presenting only scant data. One such case can be seen in Chapter III where it is stated, "An overview of stability classes with the appropriate value of m is given in Table III.1." No documentary evidence is given for the chosen values of 'm' or how the appropriateness of 'm' was determined. The reason this point is made here is the 'stability class' designation can change drastically depending on the value of 'm'. Table III.1 of Reference 1 is reproduced below.

Table III.1: stability classes and shear exponent m

Pasquill class	name	comparable stability class (TA-Luft 1986)	m
A	very unstable	V	0.09
B	moderately unstable	IV	0.20
C	neutral	III/2	0.22
D	slightly stable	III/1	0.28
E	moderately stable	II	0.37
F	very stable	I	0.41

2.3 Chapter IV: Loud Sounds in Weak Winds – effect of the wind-profile on turbine sound level

This is one of the most important chapters in the dissertation. The main hypothesis of the chapter is to show that the hub-height velocity can be higher than predicted from the 10 m high wind speeds using standard methods during stable and very stable atmospheric conditions and hence the wind turbine noise levels can be higher than expected even though the ground level velocities can be small at 2 m and 10 m heights. Such a wind-profile is possible when the atmospheric stability class is a combination of Pasquill Classes E and F with quiet winds and no cloud cover.

Chapter IV is supposed to prove the above hypothesis with scientific support.

2.3.1 Basic Assessment

The first three sections of the chapter provide background information on the Rhede wind farm in northwest Germany that abuts Netherlands. Even though, the noise assessment showed that the wind farm complies with both German and Dutch guidelines, nearby Dutch residents complained about the noise levels. The Science Shop for Physics of the University of Groningen (van den Berg's faculty) was retained to assist the residents to resolve their concerns. Section 3 presents anecdotal responses of two residents and their perception of wind turbine noise – 'pile driving sound', 'thumping sound', 'endless train sound' and such. There is no subjective polling under a blind survey to accompany the technical data presented.

2.3.2 Sound Emission and Sound Immission Levels

Long-term noise measurements were conducted at two receptor locations near the Rhede Wind Farm at two different time periods. Location A is 400 m west of the wind farm and Location B is 1500 m west of the wind farm. Wind velocities at 2 m and 10 m heights were measured only at Location A. ***NOTE:*** *It must be pointed out that wind speeds at hub-height were not measured.* The area around Location B has both low and tall trees in its vicinity. The following explanation and we quote, "As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurements data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A" was offered to justify the use of data from a far-off wind-measuring location. The above statement is heuristic at best since no data (figures and/or tables) were provided to back the above claim. Hence, it was very difficult to make sense of the data presented in the dissertation document. Similarly, meteorological data from Elde site (40 km to the west) was used to establish neutral and stable atmospheric classes for the above two sites. Even though the section states that not all Elde observations would be valid for Locations A and B, the report still used the Elde information without qualifying its validity.

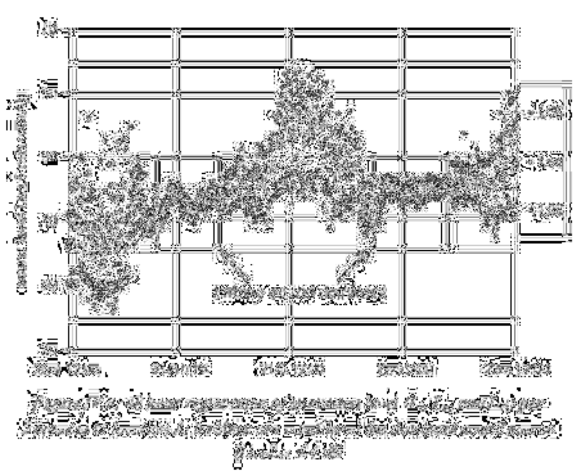
The main aim of the fourth chapter was to show that the atmospheric class during night is 'stable' or 'very stable'. The stable classes, supposedly, produce hub-height wind speeds that are higher than day time values, even though the 10 m high wind speeds could be low at night and the standard wind profiles are not able to predict the high hub-wind speeds at night. The outcome of the above hypothesis is that the night time noise levels, therefore, are higher than expected. However, as shown above, the establishment of atmospheric classes itself becomes suspect. Hence, the subjective perception that the noise levels were high may be due to low ambient sound levels during the late evening and night time hours, thereby making the wind farm noise audible.

2.3.2.1 Sound Emission Levels

Sound emission levels are the sound levels generated by the wind turbines and it is crucial to extract the levels from field measurements of overall levels. The noise levels from nine turbines were measured (Section 6) and an empirical relationship between the sound power and turbine rpm was established. The resulting sound power levels were used to calculate the noise levels at receiver locations and compare them with local measurements.

2.3.2.2 Sound Immission Levels

Sound immission, a phrase used in Europe, refers to the sound levels at receptor locations. Sound immission levels at Locations A and B were discussed in Section 7 of Chapter IV of Reference 1. The data provided is very difficult to analyse and at times very confusing. 371 hours of data for Location A and 1064 hours of data for Location B were collected. Since the monitors were un-manned, the differences in A-weighted sound levels between the 5th and 95th percentiles over 5-minute intervals were used to determine the dominance of turbine sound. The report uses a value, $L_5 - L_{95} \leq 4$ dBA, to deduce (Figure IV.4 of Reference 1) the duration of high sound levels at night time and at day time. There was no reason given as to the selection of the 4 dBA number. One would have expected a lower value, if the wind turbines were the main dominant noise sources. Actually, the value was close to 3 dB as described in Chapter V of Reference 1 (page 71 – $R_{bb,90}$ at Location P was around 3 dB). Figure IV.4 is reproduced below.

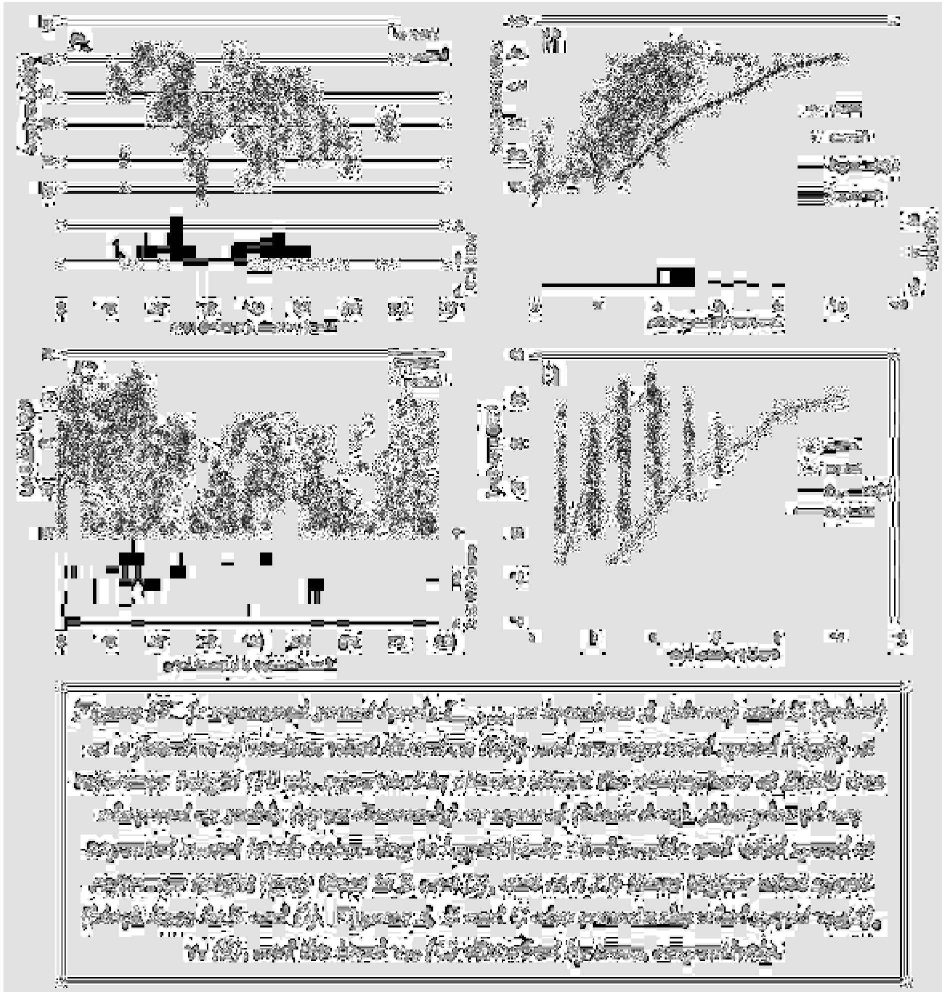


The criterion of $L_5 - L_{95} \leq 4$ dBA to determine the dominance of wind turbine noise is critical to the assessment. If the sound was steady during the 5-minute period, the above difference would be zero. Since outdoor sound levels are never steady, one would expect some variability. However, it is our belief that 4 dBA range is too high. If one were to reduce the difference to 2 dBA or 3 dBA, the night time duration for dominant sound levels would reduce substantially compared to the results presented in Table IV.3 of Reference 1. Table IV.3 is reproduced below.

Table IV.3: total measurement time in hours and selected time with dominant wind turbine sound

Location	total time (hours and % of total measurement time at location)	Night 21:00-6:00	Evening 19:00-21:00	Day 6:00-19:00
A: total	371 h	105	75	191
A: selected	92 h 25%	76 72%	9 12%	7 4%
B: total	1064 h	312	183	569
B: selected	136 h 13%	119 38%	13 7%	6 1.0%

The sound immission levels from all the measurements (the entire 1435 hours of data) were organized into the dominant turbine noise levels based on the 4 dBA difference and presented in Figure IV.5 of Reference 1, which is reproduced below. This figure with four sub-plots, is the most difficult figure to decipher. This is one of the most important figures used to conclusively provide evidence for the main argument of the dissertation. If one does not accept the 4dBA argument, the whole data structure of Figure IV.5 of Reference 1 is suspect. Further to cloud the issue, stable and neutral atmospheric classes, gleaned from Elde data (located 40 kms away) was superimposed. [Reference 1 on Page 47 does state that not all Elde data would be valid for Locations A and B, but continues, anyway, to use the invalid data to determine stability classes]. One must also infer that 'stable' classes occur only at night time and 'neutral' classes occur during the day time, even though the above was not stated explicitly in the report. No proper explanation was given for applying the above inference.



Figures IV.5 B and IV.5D Reference 1 present the variation of ‘dominant’ turbine noise levels as a function of wind speed measured at a height of 10 m. **NOTE:** It must be pointed out that no wind speeds were measured for Location B. The data points ($L_{eq,\ 5\ min}$ in dBA) were also separated into ‘stable’ and ‘neutral’ atmospheric classes. In addition, the calculated sound levels from the sound power data from Section IV.6 were also plotted in these two figures. The wind speed at 10 m height for the calculated plot was evaluated using the logarithmic wind profile of Equation III.3 shown in Section 3 of the current assessment report. Since the logarithmic wind profile was supposed to be incorrect, a corrected noise level plot, by applying a factor of 2.6, was also included in Figures IV.5B and IV.5D of Reference 1. These two figures were used to make two strong statements against the procedures used to assess wind-turbine and wind farm noise impacts.

Statement I: 'Stable' atmospheric conditions occur at night time and wind turbine noise levels are higher than expected due to high wind-velocities at hub-height.

Statement II: Logarithmic wind profile, generally used in standard procedures, is incapable of predicting current wind speeds at various heights for 'Stable' atmospheric classes, occurring at night time. And hence, these higher than expected noise levels occur at night time with low ground wind speeds, thereby, increasing the impact on residents.

However, the two figures do not provide conclusive evidence to support the above two statements for the following reasons. Contrary evidence to Statement I will be further discussed in the next section with field data from New Zealand and Australia.

a) The 'stable' and 'neutral' class designations used in the two figures are applied from a location 40 kms away and hence not valid for Locations A and B;
b) Both classes seem to produce high as well as low sound levels as clearly seen for Location B (Figure IV.5D Reference 1);
c) The light grey sound level line supposed to represent the 'neutral' class quite accurately (as stated in Chapter III of the dissertation). If that were to be true, all of the 'neutral' class data points would have collapsed near that line. However, that was not the case, as the data points are scattered all over the figures;
d) Even at a distance of 400 m from the wind farm (Location A), only a small percentage of the 'neutral' class noise levels is near the neutral line;
e) Finally, if the $L_5 - L_{95}$ value is close to 2 or 3 dBA, the entire dominant sound levels at night time could occur well below the 25% to 35% time presented in this dissertation.

As part of the current investigation Aiolos Engineering undertook a brief review of summer weather data near a wind farm located adjacent to Lake Huron in Southern Ontario. Summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months. The objective of this review was to test the rigour of the two "van den Berg" Statements I and II. Since this review was conducted in the context of the current investigation and this report, the scope of the review was limited both in its duration and site selection. The review of this data will show that limited data of the type that van den Berg relied on cannot be used to draw strong conclusions.

Aiolos Engineering compiled wind speed data from one weather station in Ontario for a period of three summer months (June, July and August 2006). The Environment Canada's weather station at Goderich, Ontario is situated within a few kms of a wind farm with 21 wind turbines. The Kingsbridge wind farm has the capacity to generate 40 MW of power. The data for the three month period was compiled in different formats and the results are presented in Appendix D. The atmospheric stability classes were approximated using the information from the AIR-EIA website (Reference 19). Even a cursory perusal of the Appendix D data would show that the correlation between stability classes and power generation is quite inconsistent. The power generated by the wind farm was obtained from the Independent Electricity System Operator's data base for Ontario (Reference 34). Unless a detailed study of the wind power generation and wind speed behaviour at the wind farm location is conducted, one cannot make strong conclusions as presented by van den Berg's work. Another salient observation from Appendix D data is that the wind farm power generation and wind speed behaviour is highly localised, controlled by the local conditions

One must point out at this juncture, that the conjectures presented in van den Berg's Statements I and II may well be true. However, the research presented in van den Berg's dissertation has not provided strong scientific evidence for the same. In addition, the data of figures IV.5 clearly shows that the sound levels at Location A, 400 m west of the wind farm is less than 40 dBA and the noise levels at Location B, 1500 m west of the wind farm, is less than 35 dBA for a substantial portion of the measurement period.

2.4 CHAPTER V: THE BEAT IS GETTING STRONGER – LOW FREQUENCY MODULATED WIND TURBINE SOUND.

Chapter V deals with the effect of frequency modulation of the wind turbine noise levels. This chapter is an important chapter since it is supposed to provide evidence that the beating phenomena gets stronger with worst results during the 'stable' atmospheric classes. The 'stable' atmospheric classes are supposed to occur only during late evening and night time hours and the turbine is supposed to generate higher than expected noise levels with the ambient sound levels at the receivers being low due to lower than expected ground speeds. The inference here, therefore, is that any modulation of higher noise levels would cause additional hardships on the receiver. This chapter aims to show that the above is true.

Chapter V is broken into 3 main sections. Section V.1 discusses the effects of atmospheric stability on wind turbine noise generation. It discusses, three possible effects, purely as theoretical conjunctures that beating (or modulation) can be due to - a) the increase in the angle of attack changes between the blade at its highest location and at its lowest location during stable conditions; or b) increase in the wind direction gradient between the blade at its highest location and at its lowest location during stable conditions; or c) reduced wind turbulence during stable conditions. No supporting experimental evidence was forthcoming. We agree that purely from theoretical consideration that the three possible mechanisms can produce amplitude modulation phenomena. But, does this happen only for 'stable' and 'very stable' atmospheric conditions and only at night time?

The other major misconception arising out of this chapter is the terms used to describe the said phenomenon – 'swishing', 'thumping', and 'beating'. The beating phenomenon in acoustics called *beat* is a special event when two sounds occur with their dominant frequencies very close to each other. A general description of *beating* is presented in Appendix E. The amplitude modulation phenomenon is different from *beating*. The acoustical principles that describe the amplitude modulation phenomenon are generally considered to be related to the movement of the turbine blades through air and the interaction of the blades with the stationary mast. In addition, the amplitude modulation could be caused by the nature of wind itself – random both in speed and direction. Irrespective of the underlying principles, the amplitude modulation produced by wind turbines is a different phenomenon from acoustical *beating*.

The UK working group on Wind Farm noise (Reference 30) studied the phenomenon of amplitude modulation and found the levels inside residential bedrooms to be below the sleep disturbance level. Importantly, the UK report recommended that further studies be conducted to understand the amplitude modulation better. [Further descriptions of the aerodynamic modulation will be presented in Section 4].

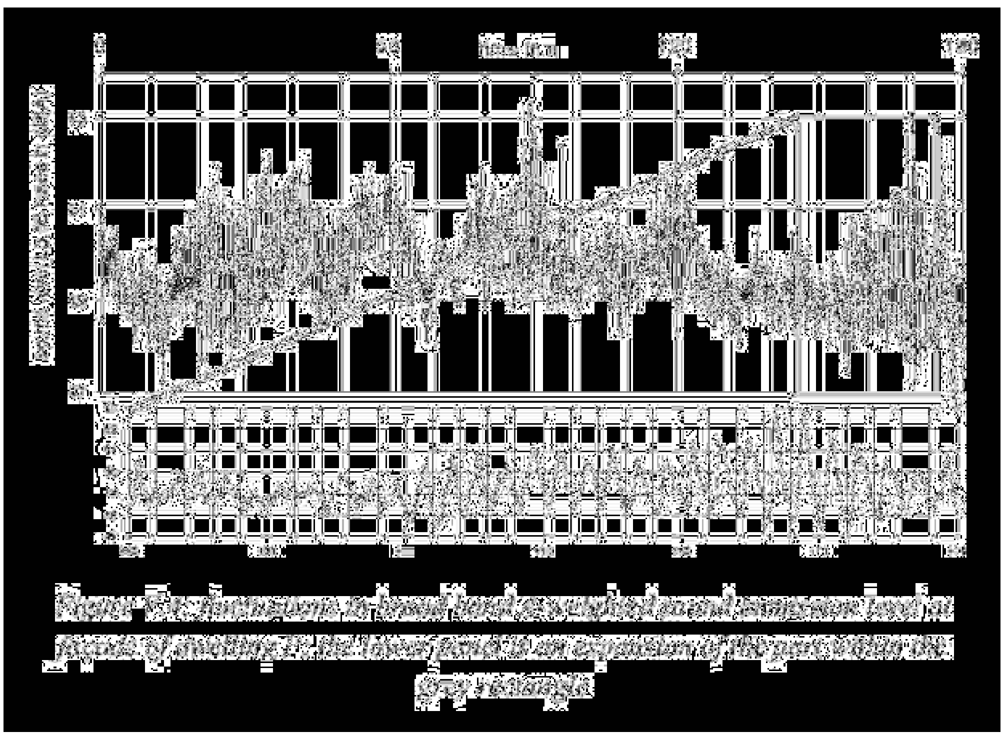
Section V.2 presents measurement at three locations; two near the Rhede wind farm and the third location (Location Z) is near a single small wind turbine. Between 10 and 15 minutes of data were collected. The measurement results are presented in terms of spectral variations. The wind velocity was measured only near one location and the wind speed data for Location Z was obtained from a number of nearby weather stations. Two conclusions were obvious from the results:

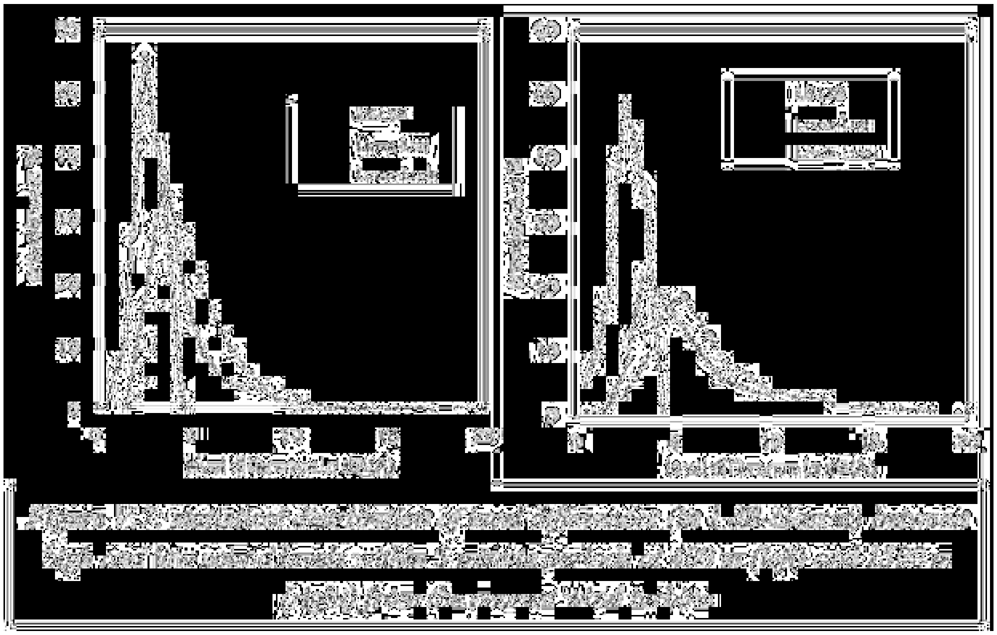
a) the infra-sound, when measured as dBG with the G-weighting scale, was found to be not audible, approximately between 15 – 20 dB below the threshold of perception, indicating that modern wind farms do not generate infrasound levels that are perceptible. For information on G-weighting network, please see Reference 31;

b) the A-weighted sound levels correlated with spectra around 400 Hz which indicates the major source is the trailing edge noise.

The main thrust of this chapter was to discuss the amplitude modulation phenomena. The modulation at Location P was audible during the measurements period, but very small at Locations R and Z. The main effect of the modulation is not to produce low frequency sounds, but change the amplitudes which are discernable by the receivers. The results showed amplitude modulation at Location P with a variation of about 5 dBA between maximum and minimum. Even though the measurements were conducted for a long duration, only 180 second of measured data was shown to prove the existence of the modulation (beating) in Figure V.4 of

Reference 1. The modulation was seen to be strong only for 30 seconds. Even though the variation was 1 dB more at Location R, no modulation was discernable. No explanation was given for these discrepancies. Even though the level variation did not indicate beating at Location R, the level variations for Locations A and B from Chapter IV were shown in Figure V.7 of Reference 1 to conjecture that modulation would happen at these locations, 28% of the time and 18% of the time respectively. Since the measurements at Locations R, P and Z were conducted at early morning hours (midnight), it was assumed to be stable weather conditions. No data was provided to substantiate the absence of modulation during other weather conditions, such as 'neutral' and/or 'unstable' atmospheric classes. Hence, one cannot immediately conclude that modulation occurs only during the 'stable' and 'very stable' atmospheric class. Figures V.4 and V.7 of Reference 1 are reproduced below,





Finally, Section V.3 discusses the perception of the modulated sound. It begins by quoting the subjective response work of Pedersen and Waye (Reference 5) that about 20% of residents would be annoyed with noise levels in the range of 37.5 dBA to 40 dBA. It then jumps to anecdotal responses of two residents near the Rhede farm. There are no studies cited in van den Berg's work that show a correlation between modulated sound and annoyance and hence van den Berg conjectures the annoyance would be worse since the expected amplitude variations make the perception of the sound strong. However, no evidence other than anecdotal responses was forthcoming.

2.5 Chapter VI: Strong Winds Blow upon tall Turbines – Wind Statistics below 200 m Altitude

This chapter deals with actual wind speed data from one site in western part of the Netherlands. The wind velocities at different heights, 10 m, 20 m, 40 m, 80 m, 140 m and 200 m were measured at half-hour intervals. The results, averaged for the entire year showed that higher wind velocities compared to the predicted wind speeds from the 10 m high wind velocity, indicating a stable atmosphere. Even the daily variations over seven days in summer months are small during the night time hours (Figure VI.3 of Reference 1, reproduced below).

The data described in Section 2.3.2.2 and presented in Appendix D was further analysed to look at the daily variations in wind speeds. In addition to Goderich weather station, the data from a few more weather stations located within 30 km radius of existing wind farms were compiled by Aiolos Engineering. Figures 2.1 thru' 2.6 show results of one-hour averaged wind speeds from three weather stations near three wind farm sites in southern Ontario. The weather data was collected at a height of 10 m above ground. The daily variations for a few summer days shown in Figures 2.1, through 2.6 seen to indicate substantial variations in wind speeds from day to day. As was explained in Section 2.3, summer data was reviewed as the main hypothesis of van den Berg is that the wind speed discrepancies due to stability classes are severe during the evening and night hours of summer months.

The measurement results of Botha [Reference 22] for four sites in New Zealand and Australia showed contradictory results of wind speed gradient. They will be discussed in Section 4. Hence, the main conclusion here is that the data presented in Chapter VI of Reference 1 is valid only for that one site in Netherlands.

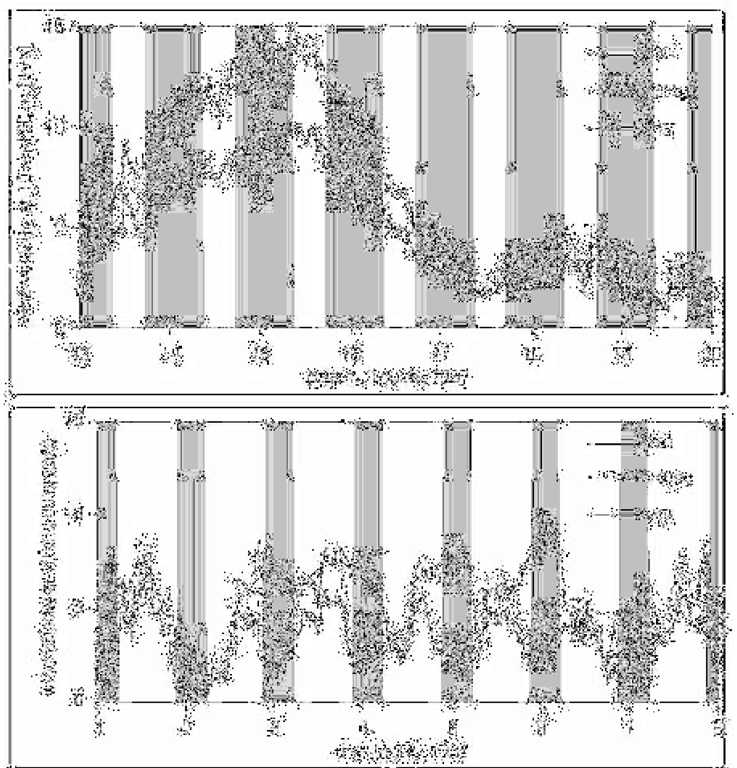


Figure VI.3: wind velocity at 10 and 80 m (solid lines), and logarithmically extrapolated $V_{80,log}$ (dotted line) over 7 days in January (top) and July (bottom); grey background: time when sun is down

The chapter then calculates expected power production at these velocities as well as calculates noise levels from the wind farm. The results show that the discrepancy for the Cabauw site between stable noise and standard logarithmic wind profiles is of the order of 2 dB. These differences are averaged from one site. The main drawback of the results of this chapter is that they are not transferable to every wind farm site in the world.

One must point out that it may be possible that during summer months stable and very stable conditions may exist at night time producing higher than expected noise levels and hence increasing the impact. However, the data presented so far does not lead one directly to that conjecture.

Figure 2.1 Elora Wind speeds

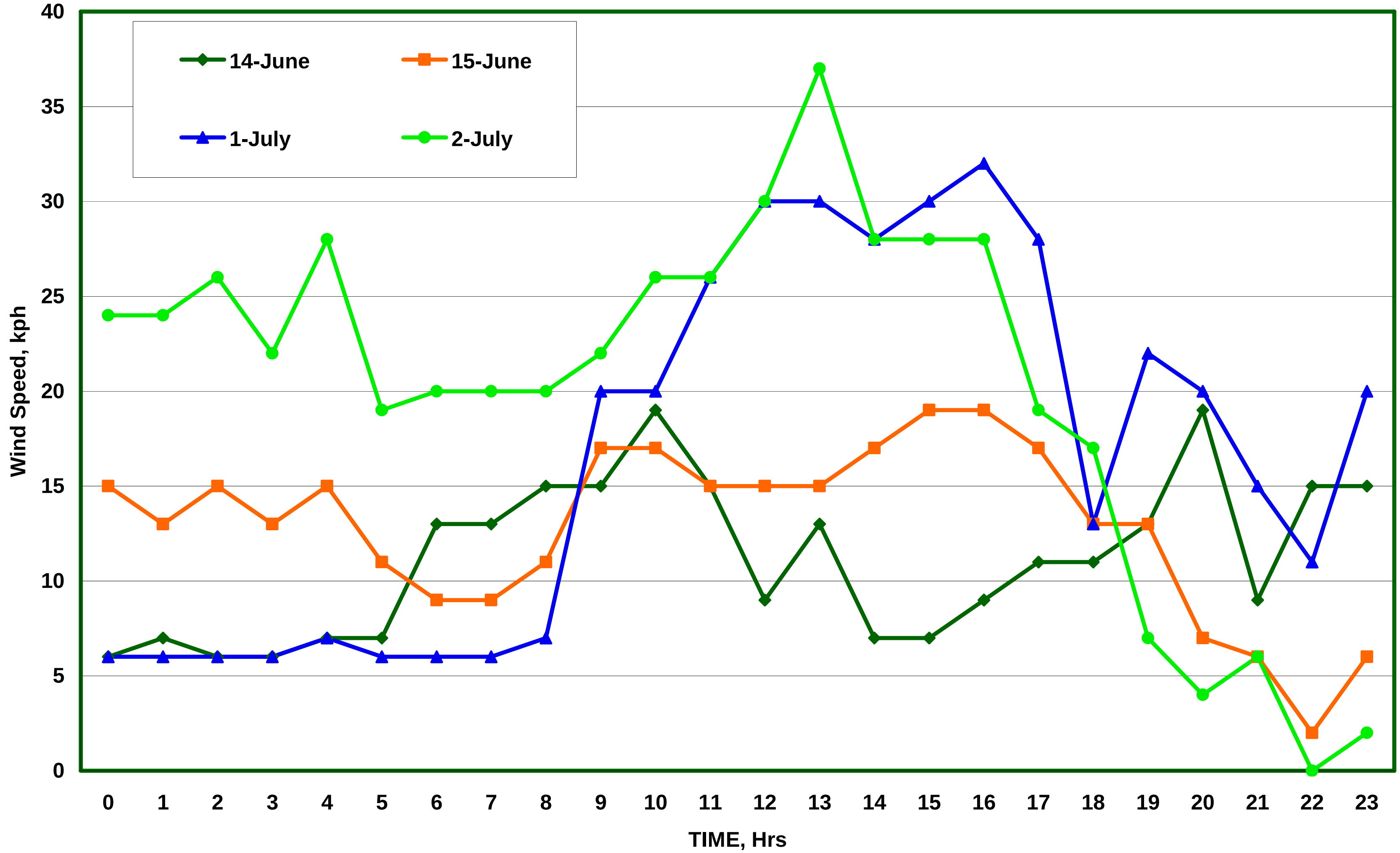


Figure 2.2 Elora Wind speeds - 2.

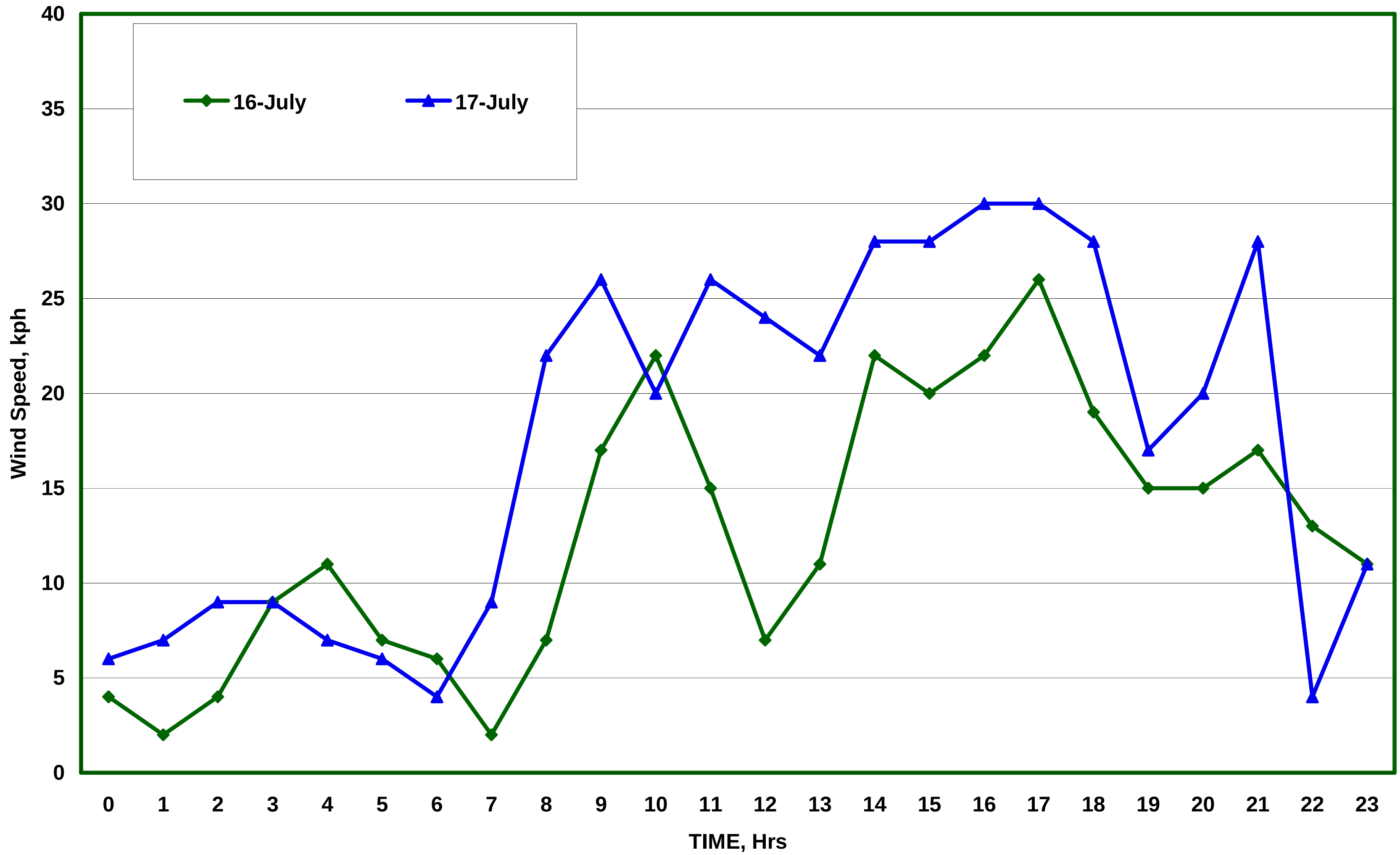


Figure 2.3 Goderich Wind speeds

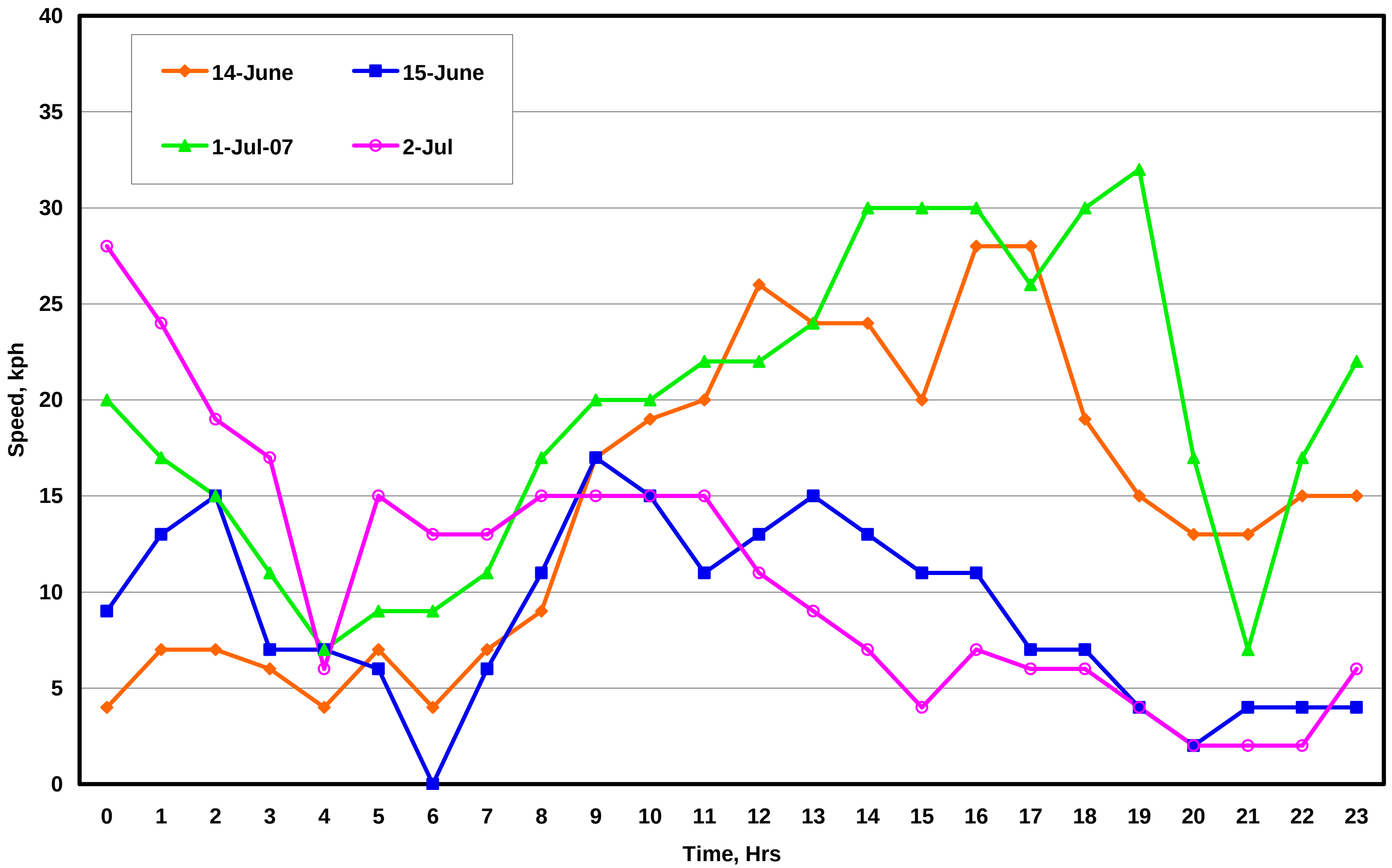


Figure 2.4 Goderich Wind speeds - 2

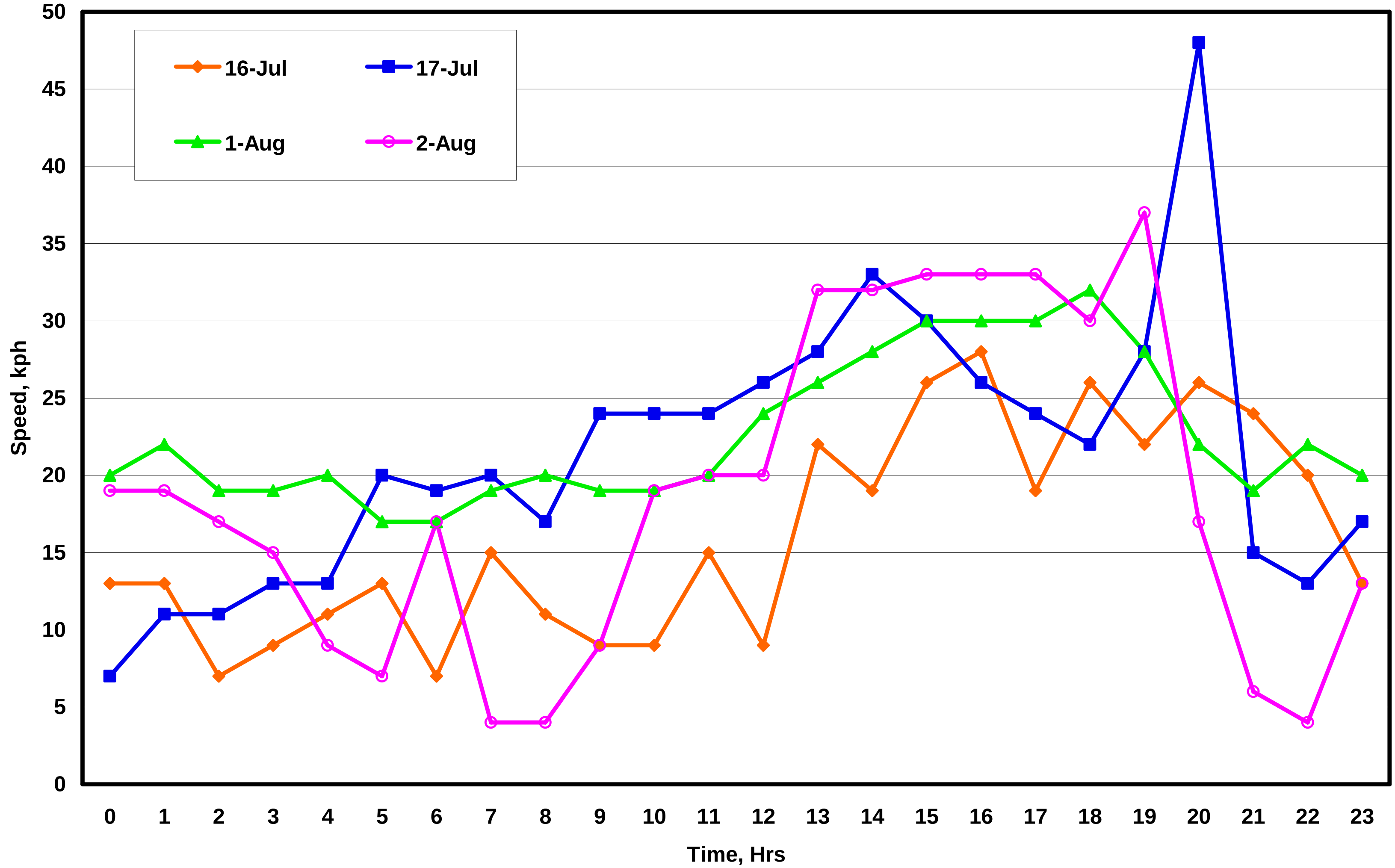


Figure 2.5 Elora and Goderich Wind speeds.

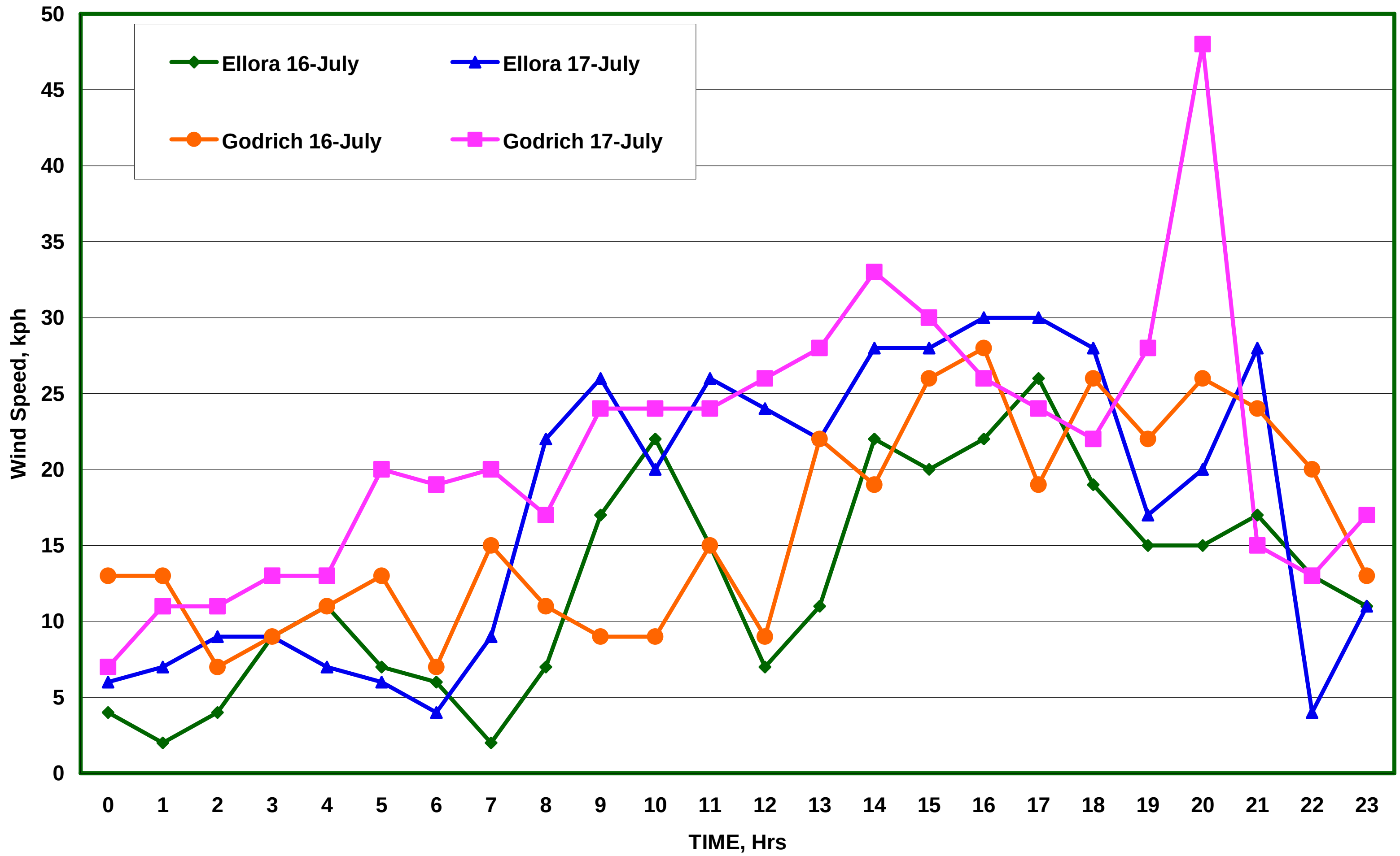
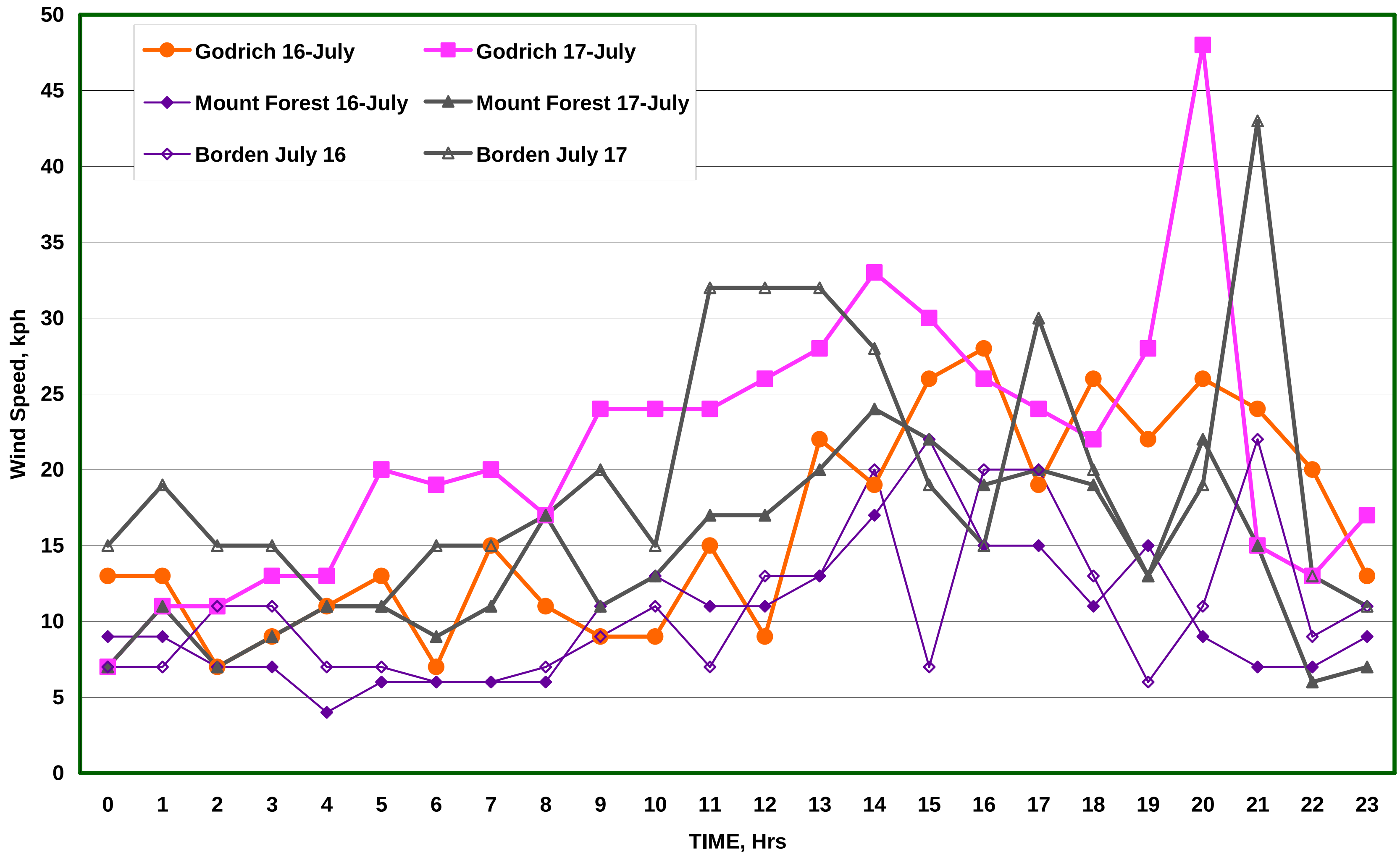


Figure 2.6 Borden, Mount Forest and Goderich Wind speeds.



2.6 SUMMARY

The doctoral dissertation of G. P. van den Berg was reviewed and comments were provided in this section. The dissertation was to provide scientific evidence for increased annoyance from wind farm during evening and night time hours. The review showed the above was not the case and the review comments are summarized below.

One of the main criticisms of the doctoral dissertation of van den Berg is that the conjectures of his research have not been supported by solid scientific data.

The major deficiencies of the doctoral dissertation are highlighted below:

A) Simultaneous noise measurements and subjective response from a random sample of the residents were not performed other than a few anecdotal responses;

B) The wind velocities at various heights were not conducted either at the turbines or near them to evaluate the atmospheric classes, but applied weather data from a location 40 kms away;

C) The wind farm noise levels at receptors were unmanned and the procedure to evaluate the dominance of turbine noise may not be correct.

D) The immission levels measured at 400 m and 1500 m distances had a large scatter to provide strong conclusions. **NOTE:** It must be pointed out that the receptor noise levels, for a substantial portion of the measurement period, were less than 40 dBA at a location 400 m away and less than 35 dBA at a location 1500 m away.

E) The *beat* of acoustics is being identified, wrongfully, with amplitude modulations and no strong evidence was provided to show the modulation gets worse at night compared to day time in the summer.

Despite the rather strong conclusions of Reference 1 some of the basic conjectures in the dissertation merit further examination. Hence, the research of van den Berg may be considered as the catalyst that started serious discussion on many aspects of wind farm noise. Future research must therefore provide stronger scientific data to validate these different noise concerns.

3.0 REVIEW OF AVAILABLE NOISE POLICIES AND GUIDELINES

The second task for the current project was to provide an evaluation of the noise policies on Wind Turbine noise applied in jurisdictions other than the Province of Ontario.

The noise policies from different Canadian provinces, USA states and a few other countries were reviewed. The regulations from Germany and the Netherlands were gathered from other review papers. [See for example Reference 18].

General comparison of the noise regulations is presented in Table 3.1.

3.1 WHO GUIDELINES FOR COMMUNITY NOISE
(Reference R1)

The community noise guidelines are the result of significant amounts of research in the relationship between noise and health. There is an understanding that noise pollution can be the cause of serious health effects through short term and long term, or cumulative, exposure. The guidelines include the values of what the World Health Organization feels to be the thresholds to health effects in various situations. The limit that has been listed in an outdoor living area, such as around a dwelling, is 50 dBA for moderate annoyance. Once the sound level has increased to 55 dBA, it is considered to be a serious annoyance. For indoors, the World Health Organization recommends the noise level to stay below 35 dBA before moderate annoyance occurs, and below 30dBA to avoid sleep disturbance at nighttime. For conditions at nighttime with an open window, the suggested limit is 45 dBA to avoid sleep disturbance. Many of the documents below reference these guidelines in the justification of selecting certain noise limits, although the Ontario Ministry of the Environment publication does not. They are also widely referred to in other literature relating to noise level limits.

Table 3.1 Comparison of Noise Regulations.

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
ONTARIO	Whichever is greatest: - Urban Areas, wind speeds below 8m/s: 45 dBA or hourly background level - Rural Areas, wind speeds below 6m/s: 40 dBA or hourly background level - Wind speeds above 8 and 6 m/s each type: wind induced background level LA_{90} plus 7dBA or hourly background level		NPC-205 or NPC-232 whichever is higher	IEC 61400-11, to be provided by manufacturer	N/A	Impact Assessment to ISO 9613 method to be submitted prior to approval for critical points of reception up to 1000 m.
Alberta	Nighttime + 10 dBA	40 dBA – 56 dBA minimum	Pre-assumed based on proximity to transportation and number of dwellings OR 24 hours, 10 min. intervals in special cases	Modeling at wind speeds of 6 to 9 m/s to achieve worst-case scenario	N/A	Noise Impact Assessment Required to be submitted for application – form given in document Noise measurements, including CSLs *recommended* for speeds 4 to 6 m/s between 1.2 and 10 m above grade
British Columbia	40 dBA at residential property		N/A	Modeling of 8-10m/s wind speeds at 10m height to be provided by manufacturer	Siting to conform to ISO 9613-2	Risk assessment required if the difference between modeled SPL and acceptable limit is close -Measurements made if complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Quebec	Sensitive Land: Type I = 45 dBA Type II = 50 dBA Type III = 55 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 55 dBA	Sensitive Land: Type I = 40 dBA Type II = 45 dBA Type III = 50 dBA Non Sensitive Land: Type IV = 70 dBA Dwelling on Industrial Land: 50 dBA	Length of time to current practiced standards – not specified. Measurements to fully cover reference intervals favoured	N/A	N/A	Measurements taken post-construction to ensure conformity, assess impact
New York (Town of Clinton)	50 dBA or Ambient + 5 dBA		Highest whole number in dBA exceeded for more than 5min per hour (requires independent certification)	IEC 61400-11 or other accepted procedures	- 500 ft from property line or road - 1200 ft from nearest off-site residence - 2500 ft from a school, hospital or nursing facility	Independent certification required before and after construction that noise limits are met.
Maine	Residential: 60dBA Comm/Ind.: 70 dBA Rural: 55 dBA	Residential: 50dBA Comm/Ind.: 60 dBA Rural: 45 dBA	Estimation based on population within 3000m radius or measurements during all hours the development will operate	N/A	N/A	Post-development one-hour equivalent measurements to be made
Pennsylvania	Fifty (55) dBA (note: this is what is in the document, not a typo here)		N/A	AWEA Standard 2.1 - 1989	1.1 x turbine height (consenting) or 5 x hub height (non-consenting)	N/A
Washington	Residential: 60 dBA Commercial: 65 dBA Industrial: 70 dBA	Residential: 50 dBA Commercial: 55 dBA Industrial: 60 dBA	N/A (Environmental noise measurement procedure is reserved)	N/A	N/A	Noise measurement only made if a complaint is filed

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Oregon	Ambient + 10 dBA		26 dBA assumed	IEC 61400-11	350m minimum, or 1000m non-consenting	
Michigan	55 dBA or L_{90} + 5 dBA		55 dBA assumed, not indicated for higher levels	IEC 61400, ISO 9613 (modeling)	1.5 x height of tower including blade in top position	ANSI S12.18 (post construction), ISO 9613 model
Australia	35 dBA or $L_{A90,\,10}$ + 5 dBA		Minimum of 2000 data points of background noise and wind speed pairs with a best fit curve	IEC 61400-11, must be overlaid on graph of background sound levels	N/A	Demonstration of compliance at all relevant receivers, if compliance is not demonstrated, operation will be restricted
New Zealand	40 dBA or L_{95} + 5 dBA		NZS 6801 (10-14 days of continuous monitoring)	Obtained from Manufacturer	N/A	Measurements taken if necessary, to follow same procedure as background levels
UK (Britain)	$L_{90,\ 10min}$ + 5 dBA OR 45dBA OR 35-40 dBA	43 dBA or 45 dBA	Minimum 7 days continuous 10 min interval monitoring	IEA Recommended Practice – using 8m/s at 10m height	N/A	Measurements made if complaint filed; no formal impact assessment required
Ireland	45 dBA or L_{90} + 5 dBA OR 35-40 dBA if L_{90}<35 dBA,	43 dBA	10 minute intervals	N/A	N/A	N/A

Jurisdiction	Daytime Limit	Nighttime Limit	Background SPL Establishment	Wind Turbine SPL Establishment	Minimum Setback	How Impact is Assessed
Denmark	45 dBA in open areas 40 dBA near residential		Annex 1 of the document; requires regression analysis of min. of 10 L_{Aeq} values measured for at least one minute each over different wind speeds	EN 45000 standards or min. of 10 L_{Aeq} values measured for at least one minute each over different wind speeds – see Annex 1 of document for full procedure	N/A	- Calculations of noise level at nearest property - Measurements after operation has begun or when deemed necessary, but not more than once per year
Germany	55 dBA/50 dBA in residential areas and 45 dBA in areas with hospitals, health resorts etc.	40 dBA/35 dBA in residential areas and 35 dBA in areas with hospitals, health resorts etc.	N/A	Recommended Practice – using 10 m/s at 10m height	-	- Calculations of noise level at nearest property, using DIN ISO 9613-2.
Netherlands	50 dBA	40 dBA (night) 45 dBA (evening)	N/A	-	-	-

3.2 NORTH AMERICAN NOISE LEVEL LIMITS AS APPLIED TO WIND TURBINES

The situation in North America in terms of noise level limits for wind turbines is currently under development. Many jurisdictions are only beginning to draft standards specifically for wind turbines, and few have gone beyond the draft stage. This is true for both the United States and Canada, where wind is still a relatively under-utilized energy source. There are a number of examples of noise level limits below from the Northern U.S. States, and some Canadian provinces, and they represent the variability from one jurisdiction to the next.

3.2.1 Ontario - Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators

(Reference R2)

The Ontario Ministry of the Environment has produced a document listing noise requirements for wind turbines. The document segregates development into three separate classes, the first two referring to urban environments, and the third referring to a rural environment. The sound level limits are dependent not only on their classification, but on the wind speed also. Where wind speeds are lower than 8 m/s in an urban environment, the hourly equivalent sound level from the wind turbine facility must not exceed 45 dBA or the hourly background sound level, whichever is greater. Similarly, in a rural environment where wind speed is less than 6 m/s, the hourly equivalent sound level must not exceed the greater of 40 dBA or the hourly background sound level. In the cases where the wind speeds exceed these levels, rather than a fixed limit, the sound level is permitted to be the wind induced background sound level, L_{A90}, plus 7 dBA. This is demonstrated in the Table 3.2 below.

Table 3.2. Ontario Noise Assessment Limits

Wind Speed (m/s)	4	5	6	7	8	9	10	11
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural)	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) - (Urban)	45	45	45	45	45	49	51	53

The noise limits apply to both daytime and nighttime periods, with the level being measured at the nearest point of reception: a location within 30 m of an existing or zoned for future dwelling. After a distance of 1000 m between the wind turbine facility and the point of reception, a detailed noise assessment is not required.

3.2.2 Alberta - EUB Directive 038 Noise Control
(Reference R3)

Of all the documents reviewed, the sound level limits for wind farms are perhaps the most complicated to determine in the province of Alberta, Canada. Primarily, the permissible sound level, PSL, depends on the location of the nearest residences. If there are no dwellings within 1.5 km, the limit is a fixed 40 dBA (this corresponds to an increase over the assumed ambient sound level of 35 dBA in rural areas). However, if there are places of residence, the PSL must be determined by the flowing equation:

$$\text{PSL} = \text{Basic Sound Level} + \text{Daytime Adjustment} + \text{Class A Adjustment} + \text{Class B Adjustment}$$

The Basic sound level is the main component of the sound level limit and ranges from 40 dBA to 56 dBA, depending on the receiving property, and is selected from a table. The daytime adjustment allows the addition of 10 dBA to the PSL during the time period of 7 a.m. – 10 p.m. The other adjustments, Class A and Class B, require technical verification to be applied, and are only done so in specific circumstances. In order to properly determine the ambient noise level and the wind farm development's noise emissions, certain procedures must be followed which are documented in the directive. For example, the ambient sound level measurement requires continuous monitoring over a 24-hour period, 15m away from the nearest dwelling. The environmental conditions at the time of the measurements are also strictly detailed. Although their sound level limits are higher than the MOE limits, similar documentation is required, such as a noise impact assessment.

3.2.3 British Columbia - Land Use Operational Policy: Wind Power Projects
(Reference R4)

The British Columbia policy regulating noise from wind turbines enforces a fixed limit of 40 dBA during all hours of the day. This limit is more restrictive than in Ontario, where allowances for higher sound levels are made when the wind speed increases. This limit is to be measured at the exterior of the nearest permanently occupied residence and/or the property line of undeveloped land zoned for future residential use. The siting must conform to ISO 9613-2, which is referenced by other jurisdictions, including Ontario, for use in impact assessment. The modeling is also similar to other jurisdictions, requiring the sound power level (PWL) to be estimated for 8-10 m/s wind speeds at a 10 m height. Should the modeling demonstrate that the estimated level is close to the acceptable limit, the policy requires that a risk assessment be conducted prior to approval. Testing of the sound levels of the facility post-construction is performed if a complaint is filed.

3.2.4 Québec - Instruction Memo 98-01 on Noise (Note: revised as of June 9, 2006)
(Reference R5)

Quebec does not have a specific document relating only to wind turbines; the applicable paper discusses noise from all fixed sources. Different limits have been assigned based on the land use of the receiving property and the residual level of noise in the area. The location of measurement is at a distance 3 m or more from reflective structures, and 0.5 m from an open window. All sound levels averaged during a period of one hour must comply with these limits. There are two main categories of land use: sensitive zones (i.e. residential, hospitals, schools) and non-sensitive (agriculture and industrial use) zones. See table below for limits. In the case of a dwelling on agricultural land, the limits for a sensitive zone apply. For dwellings on industrial land, a 50 dBA nighttime limit and a 55 dBA daytime limit will apply. In terms of sensitive areas, the noise limits are comparable to those in Ontario, although there are different levels for day and night. However, an exception is given in the case of industrial and agricultural land, unless a dwelling exists, for the sound level limits to be much higher. The sound that is measured at the receiving property is based on an equation given in the document, accounting for the equivalent sound level of the source, and corrective factors to account for impact noise, tonal noise and special situations. However, the length of time that applies is up to the discretion of the person performing the evaluation, and should correspond to the current practice methods. Similarly, when measuring background noise, measurements taken that cover the full reference range are favoured, but not required. Post construction, measurements must be taken to ensure the compliance of the facility with the appropriate limits.

Table 3.3 Noise Regulations in Quebec

Zone	Night	Day
I – Sensitive – Single family dwellings, schools, hospitals	40dBA	45dBA
II – Sensitive – Multi-residential and camping areas	45dBA	50dBA
III – Sensitive – Commercial use and park land	50dBA	55dBA
IV – Non-sensitive – Industrial or Agricultural	70dBA	70dBA

3.2.5 Oregon - Revising Oregon's Noise Regulations for Wind Turbines
(Reference R6)

Oregon has recently undergone a revision to its existing noise standards, which were last updated in the 1970s. There are two tests, or limits, that apply in the case of wind turbine developments, the Table 8 test (refers to Table 8 in the regulation) and the ambient degradation test. The authors of the revision have taken steps to coordinate their standard with that of the British and Australian guidelines on wind turbine noise. They have assumed a standard ambient background L_{50} of 26 dBA, although extensive documentation can be submitted for background noise greater than this level. The noise level limit is not allowed to increase the ambient noise levels by 10 dBA in any one hour, thus having an assumed limit of 36 dBA, which is lower than the MOE limits. It is also low enough to respect the WHO guidelines for indoor levels without accounting for sound reduction through walls. This limit applies to both daytime and nighttime, just like the MOE limits. However, unlike the Ontario requirements, there are also setbacks that must be adhered to; a minimum of 350 m for a consenting owner, and 1000 m between the nearest wind turbine and the property of a non-consenting owner. The methods of evaluating the sound created by the wind turbine development use the same methods that the majority of manufacturers provide to make things easier. The project must be evaluated under the maximum sound power level conditions according to IEC 61400-11 (8 m/s at 10 m height), but no correlation between 10 m and hub height is assumed.

Table 3.4 Oregon's Table 8 Limits, dBA

Statistical Descriptor	Daytime (7 a.m. – 10 p.m.)	Nighttime (10 p.m. – 7 a.m.)
L_{50}	55	50
L_{10}	60	55
L_1	75	60

NOTE: Maximum Permissible levels for New Industrial and Commercial Noise Sources, dBA - As in Bastasch, Noise-Con 2004, originally from OAR 340-35-035.

3.2.6 Pennsylvania - Wind Farm Model Ordinance Draft 12-08-06
(Reference R7)

The draft document developed in Pennsylvania is a model document prepared for the use by different local municipalities. It is not the regulation for the entire state. Local municipalities can use the draft document to prepare their own policies and guidelines. There is only one limit in the Pennsylvania draft, which applies to both daytime and nighttime. The sound level limit is slightly unclear however, because it states that the audible sound "shall not exceed fifty (55) dBA" (note that this has been correctly recorded here, the discrepancy between the written word and the numerical value given in parentheses). This value is much higher than the value given in the MOE regulation, and also equals the WHO recommendation for serious annoyance in an outdoor setting. [See Reference R1]. There is no mention or consideration of ambient sound levels, but waivers to this sound level may be considered. It also does not mention whether this is an hourly limit or not. The point of receiving is considered to be the "exterior of any occupied building on a non-participating Landowner's property." There are also associated setbacks that must be followed. The distance between a wind turbine and the nearest building on the same property must be a minimum of 1.1 times the turbine height. The distance between a turbine and the nearest occupied building on a non-participating property must be at least 5 times the hub height of the turbine. These setbacks exist in response to both safety and noise related issues.

Table 3.5. Pennsylvania Draft Ordinance

	Receiving Property Designation					
Source	**Residential (Class A)**		**Commercial (Class B)**		**Industrial (Class C)**	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
Class C	60 dBA	50 dBA	65 dBA	55 dBA	70 dBA	60 dBA

Note: Daytime is considered to be 7am – 10pm
Nighttime is considered to be 10pm – 7am

3.2.7 Washington - Chapter 173-60 WAC Maximum Environmental Noise Levels (Reference R8)

In Washington State, there is no specific regulation for wind turbine noise, so sound levels must comply with the limits in the environmental noise legislation. This results in noise limits that are the highest among those reviewed here (along with Maine), much higher than the MOE limits. Noise level limits are dependant upon the designation, or class, of both the source property and the receiving property. Wind turbines, as a source, would fall under neither Class A, residential, nor Class B, commercial; therefore they would be considered Class C. The hourly sound levels must not exceed the listed measures anywhere within the property line of the neighbouring property. However, it is also mentioned that local governments should adopt their own noise policies. Chapter 173-58 WAC details the proper sound level measurement procedures to follow.

3.2.8 Michigan - Michigan Wind Energy System Siting Guidelines Draft #8 (Reference R9)

The Michigan wind energy draft is meant to apply to smaller local governments and non-urban areas that do not have other existing guidelines in place. There are different guidelines for small, on-site use wind turbines, and larger developments meant for grid energy use.

The Michigan guideline considers the measure of the ambient sound level to be L_{90} and it is assumed to be less than 55 dBA in most cases. The guidelines state that the sound level generated by the turbines should not exceed 55dBA at any property line, unless with written consent. This level is similar to the one developed by the State of Pennsylvania (see above). During any one hour, this is not to be exceeded for more than three (3) minutes. Should the ambient sound level be greater than 55dBA, then the sound level limit is L_{90} + 5dBA, L_{90} as the measured ambient sound level. For demonstration of the compliance to these limits, a submission following IEC 61400 and ISO 9613 methods must be completed for project approval, and within 60 days of the project's completion, the levels must be verified to ANSI S12.18 by a professional third party. The State of Michigan is the only other jurisdiction among those reviewed that requires submission of noise impact according to ISO 9613 like the Ontario MOE requirements. However, the noise level limits are much higher than the MOE limits.

3.2.9 Maine - Chapter 375 No Adverse Environmental Effect Standard of the Site Location Law

(Reference R10)

This is another example of a state that has written a standard for use where local governments have not written their own. Local standards take precedence over the state limits unless they contain values over 5 dBA higher for the same situation. As with the Washington sound level limits, the noise limits within this document apply to all environmental noise, including wind turbines, resulting in much higher values. The noise limits apply to new and expanding developments and are measured at the property line, but no specific information is provided on how the sound levels from wind farms are to be modeled. The limits vary based on the zoning of the receiving property or the ambient sound level, and are different for day and night. The noise limits are summarized in the Table 3.6.

Table 3.6 Regulations in Maine

Receiving Property	Daytime Sound Level Limit (7am – 7pm)	Nighttime Sound Level Limit (7pm – 7am)
Any location that is not zoned for commercial, transportation or industrial	60 dBA	50 dBA
Any location that is zoned for commercial, transportation or industrial	70 dBA	60 dBA

These limits apply unless the ambient sound level prior to development is equal to or less than 45 dBA during the daytime hours and 35 dBA during the nighttime hours, such as in a rural environment. Should this be the case, the limits are required to be 55 dBA during the day and 45 dBA during the night; a 10dBA increase, regardless of the zoning of the receiving property. There are two methods allowed to demonstrate the level of the ambient sound, by performing measurements, or, if the population within a 3000 m radius of the property is greater than 300 people, the state allows the assumption that the ambient level exceeds 45 dBA during the day and 35 dBA at night. Additionally, if it can be proven that the development will not emit sound levels greater than 50 dBA during the day and 40 dBA during the night, there is no requirement to estimate or measure the sound levels.

There are further requirements for short duration repetitive sounds and tonal sounds. There are also regulations on the personnel carrying out the measurements, the instrumentation and calibration necessary, and the location, configuration and environment conditions for the microphones, but not necessarily in the specific case of applying the measurements to wind farms.

3.2.10 New York - Power Naturally: Examples of NY Local Government Laws/ Zoning Provisions on Wind

(Reference R11)

The state of New York does not have a standard for wind turbine noise, but relies on local governments to develop their own, which many have. The town of Clinton, NY, is one such municipality, and is a good indication of what the standards in New York State are like. The limit, which applies at any time of the day, is $L_{10} \leq$ 50dBA, meaning that in any one hour, 50 dBA can be equaled or exceed only ten percent of the time. The sound level is measured at the nearest residence, located off-site, which may or may not include more than one property. If the owner consents to a higher threshold of noise, a waiver can be granted allowing an increase to the noise level limit. If the ambient sound, which is defined as the highest whole number in dBA exceeded for more than 5 minutes per hour, is greater than 50 dBA, then the sound level limit is the ambient sound level plus 5dBA. These levels are higher than the MOE limits, but remain just below the level of moderate annoyance for outdoor noise of 50dBA listed in the WHO Community Noise document.

3.3 Noise Limits from Europe

Europe has long been at the forefront of developing and utilizing wind energy as an energy source. It is not surprising that they have been able to develop noise limit standards to a higher degree than North America. It does not mean that they are more complicated; in fact, they are often simpler than North American noise limits. The following are some examples of noise level limits of wind farms from European countries.

3.3.1 *UK - ETSU-R-97: The Assessment and Rating of Noise from Wind Farms* (Reference R12)

The document produced by the Working Group on Noise from Wind Farms is perhaps the most comprehensive document of all the ones reviewed here. It covers the history and philosophy of developing noise limits, as well as a thorough explanation of the current limits. The document regulates a separate limit for daytime and nighttime noise levels. These are in part based on the background noise level, $L_{A90,\ 10min}$, which is determined by continuous monitoring of ten minute intervals over a period of time, correlated with different average wind speeds measured over the same period. There is no distinction between zoning or the use of the receiving property as in the Ontario MOE limits.

The principle of the limits is that the wind farm noise is limited to 5 dBA above the wind dependent background noise level, subject to a minimum value at low wind speeds. During the daytime, this minimum value in low noise environments is not to be lower than a range between 35 dBA and 40 dBA, depending on the number of dwellings and the effect on the amount of energy produced. At night, this minimum value is 43dBA. Both of these limits are recommended to be increased to 45 dBA in cases where there is financial benefit to those involved. As with other standards, a 5 dB penalty is incurred if tonal characteristics occur. Should this appear to be the case, a tonal assessment must be performed, consisting of 2 minute measurements. The document does not require an impact assessment of the development to be submitted.

3.3.2 *Ireland - Wind Energy Development Guidelines*
(Reference R13)

Ireland has adopted noise limits that are similar to the UK limits for wind turbines. The daytime limit is allowed to be the maximum of 45 dBA or 5 dBA above the background level, L_{90}. However, if the current level of background noise is very low, below 30dBA, the noise level limit will fall in the range of 35 dBA to 40 dBA. The standard does not state how this limit will be determined. The nighttime limit is fixed at 43dBA. These noise levels are comparable to the Ontario MOE limits. The Irish Guidelines have no set-back limits. Instead it states and we quote, "In general noise is unlikely to be a significant problem where the distance from the nearest turbine to any noise sensitive property is more than 500 m." [Reference R13). The document has stated that in order to determine the ambient sound level, measurements should be taken at ten minute intervals, however, it has not dictated how the wind farm noise level should be predicted or what steps to determine the impact of the wind farm should be taken.

3.3.3 *Denmark - Document: Statutory Order From the Ministry of the Environment No. 304 of May 14, 1991, On Noise From Windmills*
(Reference R14)

Denmark's noise limits are fixed, ambient conditions having no effect, and apply to both daytime and nighttime with no distinction. This is in contrast to the MOE limits, which may depend on both the wind speed and the hourly background level; however, the actual sound level limits have a direct comparison to Ontario's. When the wind farm is located in the open country, the outdoor sound level limit is 45 dBA at the nearest neighbouring property, considered to be any residential building other than the "private house of the windmill owner". For wind farms closer to residential areas, the fixed limit is 40 dBA.

3.3.4 *Germany - Document: Lärm (Techniche Anleitung Lärm, Germany), 1998*
(Reference R15)

The German noise limits are defined in the above document and are outlined in Table 3.7 below.

Table 3.7. German Noise Regulations.

Area	Day Time	Night Time
Industrial Area	70 dBA / 65 dBA	70 dBA / 50 dBA
Mixed residential area and industry or Residential areas mixed with industry	60 dBA	45 dBA
Purely residential areas with no commercial developments	55 dBA / 50 dBA	40 dBA / 35 dBA
Areas with hospitals, health resorts etc.	45 dBA	35 dBA

Calculation of sound propagation is done according to ISO 9613-2. All calculations have to be done with a reference speed of 10 m/s at 10 m heights.

3.3.5 Netherlands: Bseluit van 18 oktober 2001, houdende regels voor voorziengen en installaties; Besluit voorziengen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487

(Reference R16)

Noise regulations specific to wind turbines in the Netherlands were issued in 2001, but are currently under review by the Dutch authorities. The 2001 wind farm noise limits followed a wind speed dependent curve and are shown in Table 3.3.2 for night time noise limits. The limit for day time started at 50 dBA and for evening hours, the limit started at 45 dBA and increased to 50 dBA for a speed of 12 m/s.

Table 3.8. 2001 Netherlands Noise Assessment Limits – Night time.

Wind Speed at 10 m height (m/s)	1	2	3	4	5	6	7	8	9	10	11	12
Wind Turbine Noise Criterion, dBA	40	40	41	41	42	42	43	44	46	47	48	50

As noted above, the 2001 assessment process is currently under review. In the interim, the Dutch authorities use their established general limits, not specific to wind turbines, of 40 dBA (night), 45 dBA (evening) and 50 dBA (day).

3.4 WIND FARM NOISE LIMITS FROM AUSTRALIA AND NEW ZEALAND

The wind farm noise limits of these two countries relate more to those of the European countries rather than North America. They require extensive data collection for the determination of ambient sound levels, and the sound level limits themselves are among the lowest, being developed in accordance with the World Health Organization document Guidelines for Community Noise. The standards as written are much more detailed in their requirements, and thus are of great value when reviewing noise standards for wind farms.

3.4.1 Australia - Planning Bulletin 67: Guidelines for Wind Farm Development and Environmental Noise Guidelines: Wind Farms
(References R17 and R18)

There are documents from both Western and Southern Australia; however, there is only one set of noise limits since the Western Australia guidelines reference the South Australian noise limits. The South Australian guidelines have elected to define fixed limits that must be followed, and are among the strictest that are reviewed here. The limit during the daytime is 35 dBA or the background noise plus 5 dBA, $L_{A90,\ 10}$ + 5 dBA. The other jurisdiction that has a comparable noise level limit is the American state of Oregon. Both Australia and Oregon have limits that are more strict than Ontario. In order to determine the ambient levels, extensive data collection of noise levels over continuous 10-minute intervals must be examined according to a regression analysis. Wind speeds must be measured at 10m above the ground and also analyzed over the same periods. In order to determine the sound level limit compliance, the sound is measured not at the property line, but at a distance of up to 20 m away from the nearest house. In addition, demonstration is required that shows the operational sound levels do not exceed the predetermined limits or else restrictive measures may be taken to limit the operation of the wind farm.

3.4.2 New Zealand - NZS 6808: 1998: Acoustics – The Assessment and Measurement of Sound From Wind Turbine Generators
(Reference R19)

New Zealand also has a fixed sound level limit, as with other countries. At any residential home, the sound level limit outside of the house must not exceed 40 dBA. This limit has been selected to achieve an indoor sound level that corresponds to the values recommended in the WHO Guidelines for Community noise. If the background noise, L_{95}, exceeds 35 dBA, then the sound level limit is permitted to be L_{95} + 5 dBA. These levels are higher than the strict limits of Australia and Oregon, and are comparable to the Ontario and Danish sound level limits. This limit is to apply at the property line of the nearest residential property, or the "notional boundary" if the dwelling is located on a large rural property. The standard allows the sound levels from the wind farm development to be estimated using the sound power levels supplied by the manufacturer, but for determination of the ambient sound levels, extensive data collection over a period of ten to fourteen days is required. Post-installation verification is not always required by the standard.

3.5 DISCUSSION

The assessment of wind farm noise and their impact on sensitive receptor locations as applied in different jurisdictions were described above. The main differences between the different regulations and guidelines are twofold:

a) The acceptable noise limits; and
b) The evaluation of receptor noise levels from the cumulative operation of the turbines in the wind farm.

The commonality among the regulations and guidelines is quite striking. All of them accept the IEC Standard 61400-11 (Reference 26) procedures to establish the sound power levels of wind turbines as well as the determination of the hub-height and/or the 10 m high wind speeds within the operating range of the wind turbines. In addition, none of them consider the effect of atmospheric classes on night time operational character of the wind farm such as higher-than-expected wind speeds at hub-height compared to the conventional wind-shear prediction methodologies.

It is seen therefore, that the main difference between the regulations and guidelines is the noise limits and hence a comparison table is given below in Table 3.8 below. Table 3.8 summarizes only the night time noise limits. Note that direct comparisons of limits may not be appropriate as different jurisdictions have different legal, procedural and assessment frameworks.

Table 3.8. Approximate Ranking of Noise Regulations (Night time limit, dBA).

Jurisdiction	Noise Limit, dBA
Australia	35 and adjusted higher with wind speeds
Germany and Oregon, USA	35 to 36
Alberta, British Columbia, Quebec, Denmark, and Netherlands (Interim)	40
United Kingdom, Ireland, Ontario and New Zealand	40 and adjusted higher with wind speeds
New York, Maine, Pennsylvania and Washington, USA	50 and higher

3.6 SUMMARY

Regulations and guidelines from different jurisdictions in North America, Europe and Australasia were highlighted in this section. These are some of the examples of different assessments of noise impact from wind turbines and wind farms. It was shown that some jurisdictions have special legislation concerning wind turbines, while others apply general recommendations. Different descriptors such as L_{Aeq} or $L_{A90,\ 10\ min.}$ were used to quantify wind turbine noise levels. The noise levels could be either absolute values or related to the background noise level. The background noise levels could be standardised, measured or related to ambient wind speeds. The review of the regulations and guidelines of the jurisdictions investigated showed that the Ontario, Canada assessment process is similar to other jurisdictions.

4.0 REVIEW OF AVAILABLE LITERATURE

A substantial portion of information, both scientific and non-scientific is available in the open literature. The literature review focussed mainly on the following:

I) Metrological effects on wind turbine noise generation;
II) Assessment procedures of wind turbine noise levels and their impact;
III) Particular characteristics of wind farm noise; and
IV) Human responses to wind farm noise levels.

NOTE: The literature review did not consider material that was available after June 2007.

The exact noise generation mechanisms of wind turbines and control techniques of wind farm and turbine noise were not reviewed by the current investigations. Relevant databases such as journals through ScholarsPortal, internet and conference proceedings were searched for the literature. Proceedings from a few conferences were searched also. It must be pointed out that conference papers are usually accepted without proper peer-reviews. Only a few articles were available and are listed in the main reference list. The results of the review are summarized below.

4.1 METEOROLOGICAL EFFECTS

The paper by P. Botha of New Zealand has shown the effects of weather conditions on wind speed profiles with height (Reference 22). This is the only paper, to our knowledge, that has scientifically shown variation of wind speeds with heights from measurements conducted at four sites – two (2) in New Zealand and two (2) in Australia. The measurements were conducted for a period of one year. The two Australian sites (Sites 1 and 2) were flat terrain and the two New Zealand sites (Sites 3 and 4) were complex terrain. Wind speeds were collected in 10 minutes intervals and the composite results from Reference 22 are reproduced below as Figure 6.1.

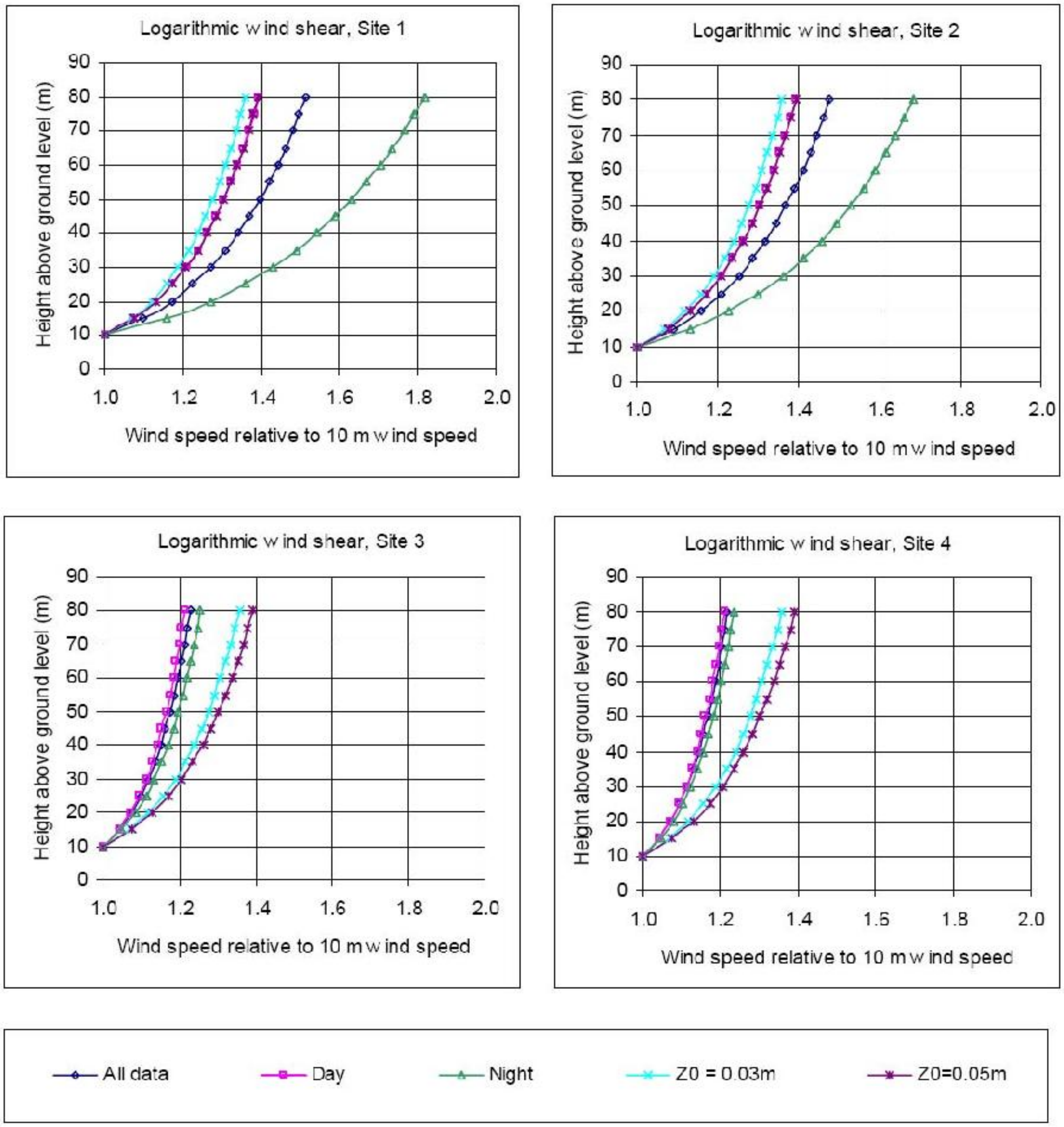


Figure 4.1. Wind speed profiles at 4 different sites

(From Reference 22 – Figure 1)

Five graphs were plotted for each site: Composite profile for all day data, profile for day data, profile for night data, IEC standard logarithmic profile with the shear coefficient from observed site conditions (Z_0 = 0.03) as well as the standard shear coefficient, Z_0, of 0.05. The results do indicate that for some terrains, the hub-height wind speeds can be more at night time than during day time when compared to the 10 m height wind speeds. However, the local conditions determine the meteorology and one cannot, as analysed by van den Berg, apply information from far-off sites to local conditions. Further, for the terrains in Australia, the Sound Power Levels at night time would be around 2 dBA more than predicted from standard procedures from day time profiles. It must also be highlighted that the measurements of Reference 22 clearly showed the wind profiles were nearly identical between day and night time for the complex terrains of New Zealand.

The main conclusions of this section are: a) wind shear is an important parameter that must be accounted for appropriately in any assessment; and b) the effect of meteorology is highly localized and strong conclusions cannot be easily transferred from site to site.

4.2 ASSESSMENT PROCEDURES OF WIND TURBINE NOISE LEVELS

Papers by Botha (Reference 22), Sloth (Reference 23) and Sondergaard (Reference 24) are examples of work undertaken to look into the assessment procedures currently applied in many jurisdictions. These three papers evaluate the application of sound power levels of wind turbines standardized to a 10 m height wind speed. The main conclusion of these papers is that the normal procedure of basing the analysis and assessment on the standardized sound power levels is not sufficient. Sloth shows a method to incorporate the relevant sound immission data with appropriate uncertainties accounted for so as to minimize noise annoyance. One such method is suggested in Appendix F. Sonderggard has also pointed out that additional research is required to account for many of these deficiencies. References 27 and 28 showed that many of the propagation models have uncertainties associated with them and can produce "less than accurate" results if local weather conditions are not properly modelled.

One of the main criticisms about noise assessment process of wind farm application is that the sound power levels of wind turbines are measured and reported following the procedures of the IEC-Standard [Reference 26]. It must be noted that the IEC 61400-11 standard for wind turbine noise is a measurement standard and is primarily intended to define how manufacturers obtain and report the sound power from wind turbines under standardized wind shear conditions. It does not prevent one from adjusting the sound power to reflect the actual site specific wind shears obtained from testing.

4.3 PARTICULAR CHARACTERISTICS OF WIND FARM NOISE

Two main issues are usually discussed regarding the source characteristics of noise generated by wind turbines – low frequency or infra sound and the swishing (thumping) sound normally termed as the amplitude modulation phenomenon.

The measurement results from wind turbines, such as the data reported by van den Berg (Reference 1) and Howe and McCabe (Reference 28) show the absence of significant low frequency components and the same conclusion is highlighted by Regan and Casey ((Reference 25) in their primer on wind turbine noise aspects. The results of Reference 1 (van den Berg's dissertation) show that the infra-sound levels, even if present, are well below the threshold of perception.

The nature of the amplitude modulation phenomenon and its relationship to the acoustical *beating* phenomenon was already discussed in Section 2.4. The different principles of these phenomena will not be discussed further. Due to the nature of the amplitude modulation phenomenon, the swishing or thumping exists all the time. Only van den Berg has attempted to show that the modulation gets stronger at night time. Our review of van den Berg's work was presented in Section 2. We were unable to find other works in the literature that provide evidence for increased modulation at night time. The only effect, discussed in the next section, of the phenomenon is the modulated sound becomes audible at night time. This could be due to quieter ambient sound at night time. As Reference 18 states, "In summary, the modulation in the noise from wind turbines is not yet fully explained and will not be reduced in the near future and is therefore a factor of importance when discussing noise annoyance from wind turbines."

Reference 30 has addressed the issues connected with modulation. One of its principal findings is and we quote, "the common cause of complaint was not associated with low-frequency noise, but the occasional audible modulation of aerodynamic noise, especially at night. Data collected showed that the internal noise levels were insufficient to wake up residents at these three sites. However, once awoken, this noise can result in difficulties in returning to sleep." Reference 30 does not use the term "beating" to describe the amplitude modulation that has been observed as well as measured. It has been referred to simply as "aerodynamic modulation." Reference 30 also points out that the many mechanisms hypothesized by van den Berg (Reference 1) for the modulation behaviour are debatable. It was shown in Section 2 during the current investigation that the data provided by Reference 1 do not support its findings. Further, no support was seen for the modulation behaviour to get stronger under stable atmospheric classes at night time as postulated by van den Berg. The same points were presented in Section 2 of this report. Finally, Reference 30 discussed the many possible mechanisms that can cause the amplitude modulation as well as provided measurement results to show that modulation can produce changes in noise levels of the order of 10 dB. It concluded that detailed research is required to settle many of the unknowns that can cause the amplitude modulation.

4.4 HUMAN RESPONSES TO WIND FARM NOISE LEVELS

A considerable body of literature is available on this subject, both scientific and anecdotal. Only a few of the scientific and review articles, References 5, 12, 18, 20, and 25, are highlighted in the current study.

According to Reference 25, the only health effect of wind turbine noise is annoyance. Sheppard et al. (Reference 12) conducted a laboratory study with unbiased subjects and played different sounds including wind turbine noise at various levels. Since the study was conducted in early 80s, the old type wind turbines were included in their investigations. Their study developed a human response criterion for wind turbine generators based on receptor received noise levels and termed it 'Perception Detection Threshold.' The study showed that the thresholds for wind turbine noise were below the thresholds of general tones. After validating the usefulness of the response function, the following annoyance table, based on an old ISO standard, now defunct, was recommended to evaluate the community response. The annoyance table is presented in Table 4.1 below.

Table 4.1 Estimated Community Response to Wind Turbine Generator Noise

(From Reference 12 –Figure 12 of Reference 12, based on an ISO standard)

Amount in dB by which the rated noise exceeds Threshold Level	Estimated Community Response	
	Category	Description
0	None	No Observed Reaction
5	Little	Sporadic Complaints
10	Medium	Widespread Complaints
15	Strong	Threats of Community Action
20	Very Strong	Vigorous Community Action

NOTE: **Rated Noise Level –** The actual noise level that would be measured at the receptor locations;
Threshold Level – The average ambient sound level that would exist in areas around the wind farm site.

A study, similar to that of Sheppard (Reference 12) is required to evaluate the detection threshold for modern wind turbines.

The annoyance study of Pedersen and Waye concluded that annoyance increases with sound levels. However, these annoyance studies have very small sample sizes and focussed on subjects living close to wind farms. No blind survey was conducted. Only 65 of the 356 respondents were exposed to noise levels of 37.5 dBA and above. The following categories – perception, dose-annoyance, sensitivity, attitude to source, visual exposure and rural setting – were included in the survey. The correlation between most of the categories and noise levels were small. The noise level and annoyance response was proportional to the exposure level. However, the sample size was too small. The subjects had prior exposure to wind turbines, making the sample biased. It must be acknowledged that the research of Pedersen and Waye has provided important insights into the human response of wind turbine noise and has considered important parameters.

However, the work of Pedersen and Waye need to be expanded to include large enough samples with unbiased subjects.

Finally, one of the arguments presented by anti-wind farm proponents is that ‘beating’ increases human annoyance. The only result that can be culled from the literature, Reference 18, is that the modulation frequencies, 0.5 to 1 Hz for wind turbines, are such that the wind turbine noise can be detected. Since major studies on wind turbine beating and human annoyance have not been conducted, major conclusions are not possible at this stage.

4.5 SUMMARY

Available literature on wind turbine noise was reviewed and the review focussed on four categories, considered important to the Ministry’s stated goals. The results of the review were presented in this section. The main findings of this section are:

A) The local terrain conditions can influence meteorological conditions and can affect the expected noise output of the wind turbines;

B) Assessment procedures applied in different jurisdictions are quite similar in their scope;

C) Wind farm noise do not have significant low-frequency (infrasound) components;

D) Further study needed in order to determine effect of modulation on human annoyance.

5.0 REVIEW OF MOE'S NOISE POLICIES AS APPLIED TO WIND FARM NOISE

The Ministry of the Environment released a guideline document, "Interpretation for Applying MOE NPC Technical Publications to Wind Turbine Generators" in 2004. The above guidance document was to assist proponents of wind turbine installations in determining the list of necessary information to be submitted when applying for a Certificate of Approval (Air and Noise) under Section 9 of the *Environmental Protection Act*. A summary of these interpretations by John Kowalewski was also published in the Canadian Acoustics Journal (Reference 33). The noise guidelines in MOE publications NPC-205/NPC-232 as well as the wind generated noise levels were applied to set the noise limits. These three documents are enclosed in Appendices A, B and C.

5.1 MOE'S ASSESSMENT PROCESS

The assessment procedures of MOE are summarized below for completeness sake:

I) All wind farm applications must obtain a Certificate of Approval from MOE. If individual wind turbines have a capacity of 2 MW or more, the project must undergo an Environmental assessment review;

II) If there are no receptors within 1000 m of the wind farm boundary, no detailed noise assessment is necessary;

III) The noise limits are established based on the location of the receptors in Class 1 & 2 areas and Class 3 areas.

IV) The sound power levels of the wind turbines are to be obtained from the standard procedures contained in IEC Standard 61400-11, by applying the wind speeds at 10 m height above ground. [Reference 26].

V) The sound pressure levels at each receptor location are to be evaluated applying the procedures of ISO 9613.

VI) The noise impact is assessed by comparing the predicted noise levels at individual receptor location with the noise limits established in Step III. The noise impact is evaluated at each wind speed over the operating range of the wind turbine specifications.

The noise limits are wind speed dependent and are summarized in Table 5.1 below.

Table 5.1 Ontario Noise Assessment Limits

Wind Speed (m/s) @ 10 m height	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Wind Turbine Noise Criterion NPC-232 (dBA) (Rural) – Class 3 Areas	40	40	40	43	45	49	51	53
Wind Turbine Noise Criterion NPC-205 (dBA) (Urban) – Class 1 & 2 Areas	45	45	45	45	45	49	51	53

The MOE procedures outlined in Appendix A do not explicitly discuss the application of penalties for source character or apply particular meteorological conditions.

The MOE's assessment process is very similar to the procedures applied in the New Zealand (Reference R19), as it recognizes the usefulness of masking effects of ambient wind. The implicit assumption is that it is the ambient wind that generates the noise of wind turbines as well as background noise levels at receptor locations.

The Ministry's noise assessment guidelines for stationary sources of sound are based on the premise that noise from the stationary sources may be annoying when it is audible over and above the level of the so-called "ambient" or surrounding environmental "noise climate" at a particular location. However, audibility does not necessarily mean annoyance. Furthermore, annoyance is not the same for the entire population; people at the extreme of the statistical distribution may be annoyed at different noise levels. Such an approach was considered a 'sound' policy from the inception of the Model Municipal Noise Control by-Law issued by MOE in August 1978. The policies provide adequate protection from adverse noise pollution impacts as well as not imposing restrictive conditions on industrial noise sources. However, the MOE's assessment, even though has provided a very simple procedure, has been very general in its overall scope. Two issues need to be resolved and are highlighted below.

5.2 PENALTY FOR SOURCE CHARACTER

The guideline document that deals with noise assessment of wind turbines, enclosed in Appendix A, does not explicitly discuss penalties for characters such as tonal components of the wind turbine noise levels, even though reference to NPC-104 is included in the interpretation document. Further, the Ministry document, NPC-205 (enclosed in Appendix C) contains guidelines for penalties, which must be used if a particular wind turbine was found to contain tonal components. The implicit assumption is that the modern up-wind wind turbines have no dominant tones in their spectrum. It must be pointed out that most of the measurement results do show that the turbine noise spectrum is devoid of dominant tones. However, MOE needs to clarify and include source character adjustments in the main body of the interpretation document and even make references to the procedures contained in the IEC Standard (Reference 26) that are used to determine the presence of tones in the noise spectrum.

5.3 METEOROLOGICAL CONDITIONS

One of the main arguments posed by van den Berg (Section 2) is that meteorological condition affect wind speed profiles with height and that the hub-height wind speed may be higher than predicted with the 10 m high wind speed being low. It was made clear in the review presented in Section 2 that the evidence presented to support these arguments were tenuous at best. However, the works of Botha (Reference 22) and Sondergaard (Reference 24) showed that local terrain conditions can dictate the wind profiles and the measurements of Reference 22 has shown that in flat terrains, the wind speed profile with height cannot be predicted accurately by standard methods such as the logarithmic shear function applied in Reference 26.

It is therefore, possible that, for a ‘worst-case scenario’, the hub-height velocities can be higher than expected thereby resulting in higher-than-expected noise levels with lower masking effect of the ambient wind at receptor locations. Some preliminary evaluations presented in Reference

32 showed that discrepancies of the order of 3 dBA are possible. Such a scenario needs to be accounted for in the Ministry's future updates of the assessment procedures. One example of a possible assessment procedure is described in Appendix F.

5.4 SUMMARY

The assessment procedures, currently, applied in the Province of Ontario by the Ministry of the Environment to evaluate wind farm noise levels were reviewed. The results showed that the procedures may have to be revised to incorporate additional factors. One possible assessment process is suggested Appendix F.

6.0 CONCLUSIONS

As part of the review process of their assessment procedures, the Ministry of the Environment for the Province of Ontario has instituted a work project with different tasks. Four individual tasks were part of the review process.

The results of each of the tasks were presented in the previous sections. The conclusions for each of the tasks were included at the end of the relevant sections. The basic conclusions are summarized below:

A) The research work undertaken by G. P. van den Berg didn't provide scientific evidence to support the few major hypotheses postulated concerning the wind turbine noise characteristics. However, the work of other researchers showed that local terrain conditions can impact the local meteorology and thereby the resulting noise levels;

B) Assessment procedures applied in different jurisdictions showed the current Ministry of the Environment process is similar to other jurisdiction. Further, the MOE process has provided a balanced approach between noise impact and the need for wind farms, based on currently available scientific data.

C) Literature review showed that additional research is still required to make definitive conclusions about wind turbine noise impacts as well as human response to wind farms. In addition, detailed research on meteorological conditions, and their impact on sound generation needs to be undertaken to realise definitive conclusions;

D) The Ministry of the Environment's procedures to assess wind farm noise levels follow a simple procedure that is sound for most situations. However, additional concerns still need to be addressed in the next round of revisions to their assessment process. These revisions may need to be addressed after the results from future research provide scientifically consistent data for effects such as meteorology, human response and turbine noise source character.