BEFORE THE PUBLIC UTILITIES COMMISSION
OF THE STATE OF SOUTH DAKOTA

IN THE MATTER OF THE APPLICATION BY PREVAILING WIND PARK, LLC FOR A PERMIT OF A WIND ENERGY FACILITY IN BON HOMME COUNTY, CHARLES MIX COUNTY, AND HUTCHINSON COUNTY, SOUTH DAKOTA, FOR THE PREVAILING WIND PARK PROJECT

EL18-026

PREFILED TESTIMONY OF RICHARD R. JAMES

ON BEHALF OF INTERVENORS

Q: Please state your name, title, affiliation, and address.

A: My name is Richard R. James. I am the Principal Acoustician for E-Coustics Solutions, LLC, in Okemos, Michigan.

Q: What is the purpose of your testimony?

A: I am testifying to the acoustic issues of appropriate thresholds for audible and in-audible wind turbine sound at non-participating properties in the footprint of the proposed Prevailing Wind Park Project (PWPP) and to the computer modeling used by the applicant to assess impact of noise.

Q: What is your educational and professional background?

A: I have a degree in Mechanical Engineering with emphasis on noise control and acoustics. I have attached a set of documents that provide the details of my professional work. (See Exhibit 1.) The first page of that packet summarizes my work with focus on wind turbines since 2006 when I formed my current company, E-Coustic Solutions, LLC, (E-CS). It summarizes my published papers and qualifications to speak to wind turbine noise measurement, modeling and the impact of wind turbine noise on people in various jurisdictions. The next page is an excerpt from a Business Week article on my work with my clients using a computer model I developed with my first company based on the work I did for my undergraduate thesis. This model was accepted in government hearings in 1976. It was capable of modeling both in-facility worker noise and community noise. I was one of the first acousticians to use computer models for new facility design long before there were established national standards for such work. Other parts of the package cover my professional credentials and affiliations, list my publications and list hearings that I have participated in over the past 10 years.

Q: What experiences have you had that qualify you as a health expert in cases involving wind turbine noise?

A: I began looking at wind turbine noise as a special case of noise source shortly after closing my last company in 2006. Several early projects resulted in media exposure and I began to get requests from many places, some international, to advise local agencies or intervenors on proper siting methods. Because of that early work I have been involved in many major lawsuits about wind turbine noises where I have had access to not only my research work but also that of the opposing acousticians through discovery. I was also involved with the early studies that found that modern utility scale wind turbines emitted a pressure pulsation caused by the blade when it passes in front of the tower back in 2009.

This experience led to my work for the intervenors in the Wisconsin Brown County Shirley Wind case which Mr. Hessler referred to in his written testimony submitted in prior proceedings before the PUC. Subsequent to that I have been associated with other acousticians around the world, such as Steven Cooper of Australia's Acoustics Group who have reproduced my work and expanded upon it.

This experience gives me a unique set of experiences that I have used to advise my clients for projects currently under development or for lawsuits related to existing projects.

Q: What materials have you reviewed in this matter?

A: I have reviewed:

1. The sound study conducted by Burns & McDonnell Engineering Company, dated May 18, 2018;
2. The contour maps of the Project depicting the 45 dBA Leq boundaries from the sound study model;
3. The pre-filed testimony of Chris Howell, summarizing his and the Burns and McDonnell Engineering report assessing noise from the Prevailing Wind Park Project (PWPP);
4. The pre-filed testimony of Dr. Mark Roberts regarding Prevailing Wind Park;
5. The testimony of David M. Hessler, dated May 4, 2018, regarding his review of the Dakota Range Wind Project and recommendations for noise thresholds;
6. The testimony of David M. Hessler, dated March 28, 2018, regarding the Crocker Wind Farm; and
7. Bon Homme County's Article 17, regulation of wind energy systems (WES).

Q: After reviewing those materials, what is your overall impression regarding any potential health risks posed by the proposed Project?

A: The project, as proposed, has a significant potential to cause adverse health effects related to sleep disturbance and annoyance to audible sounds from the wind turbines, especially at night. The recommended thresholds by Howell and Hessler of 45 dBA Leq, are not appropriate for rural communities. This is especially true for communities that have no prior experience with utility scale noise sources operating 24/7/365 that produce fluctuating, pulsatile, tonal infra and low frequency sound. Wind turbine noise emissions have specific characteristics that make them more likely to cause these adverse effects than other common rural noise sources. Thus, criteria intended for urban/suburban communities where traffic noise is the typical nighttime noise source (urban hum) are not suitable for communities were people have an expectation of quiet. People in rural communities have lifestyles that are based on the quiet nature of most rural communities at night. This is reflected in ANSI-ASA S12.9 Part 4 "Noise Assessment and Prediction of Long-term Community Response" Appendix F, which cautions:

> **"F.3.4.1** In newly created situations, especially when the community is not familiar with the sound source in question, higher community annoyance can be expected. This difference may be equivalent to up to 5 dB.
>
> **"F.3.4.2** Research has shown that there is a greater expectation for and value placed on "peace and quiet" in quiet rural settings. In quiet rural areas, this greater expectation for "peace and quiet" may be equivalent to up to 10 dB.
>
> **"F.3.4.3** The above two factors are additive. A new, unfamiliar sound source sited in a quiet rural area can engender much greater annoyance levels than are normally estimated by relations like equation F.1. **This increase in annoyance may be equivalent to adding up to 15 dB to the measured or predicted levels." (Emphasis added)**

The community's response to the wind turbine noise will be as if the wind turbines were 15 dB louder than what is being predicted. This caution was in the EPA's 1974 Levels Document and also is present in current ISO standards followed in the EU and other countries. It is accepted acoustical practice that is overlooked by wind energy developers and their consultants.

Q: Are there sound level limits that you find more appropriate for rural communities?

A: In 2008 I worked with George Kamperman, one of the senior acousticians who led in the development of community noise limits for urban and suburban communities in the 1960s and 70s, to determine what the proper sound limits should be for wind turbines in quiet rural communities. Wind turbines were never considered when the community noise limits were set and especially it was not anticipated that they would be located in quiet rural areas near homes. So we decided to apply the same type of analysis to wind turbine noise as had been done for other common community noise sources in the past. We looked at when the turbines would operate, what the nighttime background sound levels would be in the receptor's location, and how much sound they emit in each frequency band. Then applying methods for calculating sound propagation that reflect how low frequency sound differs from higher frequency sound, we estimated the distances needed to prevent the noise of ten (10) wind turbines of the 1.5 MW class common in the late 2000s from causing nighttime annoyance inside a home with windows open.

We determined that the maximum sound level for audible sounds should be 35 dBA

(Leq) and 50 dBC, especially for nighttime wind turbine noise. We also limited the new noise source to be no more than 5 dBA louder than the pre-operational background sound level at night. Typical nighttime background sound levels are under 30 dBA (L90) in these communities so the 35 dBA acts as an upper limit.

The Kamperman/James document was subsequently reviewed in a paper titled: "Noise: Wind Farms," by three experts (Shepherd (Psychoacoustics), Hanning (Sleep Medicine Specialist) and Thorne (low frequency acoustician)) and published in the 2012 edition of the Encyclopedia of Environmental Management. They review the special character of wind turbine noise and in the Appendix update the criteria that Mr. Kamperman and I prepared in 2008 to address the fluctuating character of wind turbine noise. I have attached a copy as Exhibit 2 of their paper for the details behind these criteria.

Q: Are there other acousticians who have made similar recommendations for noise thresholds in rural communities?

A: Yes, there are many who have made similar recommendations. In 2017, Dr. Paul Schomer, the Emeritus Director of the Acoustical Society of America's Standards Committee published a paper titled: "A possible criterion for wind farms" at the 173rd meeting of the Acoustical Society of America. (*See* Exhibit 3.) Dr. Schomer, in his capacity as Director of the ASA Standards Committee has directed the work of the American National Standards Institute (ANSI) groups that produce the S12 consensus standards on how to measure noise and how noise affects people for over 30 years.

In his 2017 paper, he reviews how proper application of the ANSI standards for assessing the impact of a new noise source on a community to avoid adverse impacts results in a criterion of 36 to 38 dBA Leq. Dr. Schomer explains how the character of wind turbine noise requires lower limits than other common community noise sources.

He also bases his recommendation on the findings of a major study conducted by Health Canada (the Canadian equivalent to the US Centers for Disease Control (CDC). That study looked at a sample of just under 2000 people living within 3-5 km of six wind projects in Ontario. It found that the percent of people who report they are highly annoyed by wind turbine noise jumps dramatically from less than 2% when the modeled sound levels are 35 dBA Leq or less to over 10% for levels between 35 and 40 Leq. Health Canada defines High Annoyance to noise as an adverse health effect in accordance with the World Health Organization (WHO) and other bodies. The limits for new wind projects in Canada are set at 40 dBA Leq (worst case one hour). Thus, if PWPP is permitted to produce higher sound levels, it should be expected that annoyance will also be higher for those closest to the turbines.

Other countries, such as the U.K., Australia, and New Zealand, also use 40 dBA Leq as the upper limit for wind turbine projects. Some, like Germany and other European countries have limits of 35 dBA Leq for rural communities. Limits like these have not prevented wind energy development in those countries. The developers have to select locations where there is sufficient distance to prevent noise from exceeding the limits or work out private easement contracts with neighbors.

Q: Has the use of a limit of 40 dBA Leq been found adequate to prevent adverse effects?

A: No. This might be anticipated from the Health Canada finding that 10% of people find sound levels in the range of 35 to 40 dBA Leq are highly annoyed, increasing to about 14% for higher sound levels. Jurisdictions that set the threshold at 40 dBA Leq must deal with ongoing complaints, threats of legal action and other indicators that 40 dBA Leq is not sufficiently protective. Proper siting criteria can prevent this.

Q: How can, what appears to be a small change in sound level from 40 Leq to my 35 dBA Leq or Dr. Schomer's 36-38 dBA Leq, make such a difference in acceptability?

A: While it may appear that the difference is only a few decibels, it is important to remember that a 3 dB change in sound levels represents a doubling or halving of the acoustic energy. Thus, a change from 40 dBA to 37 dBA Leq is equivalent to turning off half of the wind turbines in a project designed to meet the 40 dBA Leq limit. This implies that the 3 dB change increases the setback distances by a substantial amount.

Based on my experience reviewing Ontario projects designed for 40 dBA Leq the closest homes to wind turbines have setbacks of about 1800 feet. To meet a 37 dBA Leq limit these setbacks would be increased to about 2500 feet. To meet the 35 dBA Leq limit the setback distance would be on the order of 3600 feet. To prevent annoyance during nighttime periods from multi-turbine projects Mr. Kamperman and I calculated the setback would need to be 1.25 miles (2km).

This is primarily because the rural areas are so quiet at night that even at these distances wind turbines can be audible inside homes where people are sleeping, especially those that sleep with windows open. To avoid this disturbance, the people would need to change their behavior to how suburban people cope with noise by having windows closed much of the time and using air conditioning for summer cooling.

In parts of Germany and Poland noise limits have been replaced with arbitrary setback distances based on the diameter of the wind turbine's rotors. The setbacks are equivalent to ten (10) times the rotor diameter. Thus, for a wind turbine with a 110 meter diameter blade the setback would be about 3600 feet. This is equivalent to the setbacks derived for 35 dBA Leq limits discussed above but avoids the complexity of sound modeling.

Q: Should these limits be applied to the property lines or to the homes?

A: I am a strong supporter of property rights and believe that noise that exceeds known safe levels should not be imposed on people just because they live near a neighbor who wishes to host wind turbines. This position influences my response to this question.

If a person owns property that is primarily agricultural with a residential home, they should still have the entire property protected to prevent future restriction on how the land can be used. For example, in the future they decide to subdivide their property for residential purposes. If the limit was set to the home, it is possible that the future development would be in a location where the noise is excessive for residential land use. If the limits are set for the homes, not the property lines, then wind project's noise emissions physically trespass on the neighbor's property without any compensation for the non-participating neighbor. The phrase "Noise Trespass" has been used in states like Michigan and Ohio were the debate over setting limits for the property line vs home are debated.

The question may be easier to answer if we look at other forms of pollution than noise. Take water pollution for example. If a farmer raises livestock and that livestock causes pollution of a stream passing through the property, the adjacent property owner is deprived from using the stream for normal purposes. In most states that I am aware of, the pollution is controlled at the emitter's property line. The same should be true for noise pollution. The landowner hosting the wind turbine may have a right to have a wind turbine on his/her property but does not have any rights to allow that sound energy to trespass onto the properties of neighbors. The obligation to prevent that trespass is on the property owner hosting the wind turbine(s) and the utility operator.

There is nothing that prevents the utility developer from working out an agreement with non-participating property owners to compensate them for allowing higher sound levels on parts of their property that are between the home and property line that they know will not be used for residential developments. Thus, the property line should be the default for protecting neighbors. If the utility developer/operator is willing to provide compensation for the "Noise Trespass" they can work out arrangements to protect that part of the property that is residential or may become residential in the future.

Q: What other characteristics of wind turbine sound emission affect adjacent properties?

A: The limits using dBA criteria are focused on sound that is in the speech frequency range. Sounds that are heard. The A-weighting process de-emphasizes low frequency sounds from 500 Hz and below. That includes sound that is felt. Like the bass beat from a neighbor's home when they play the stereo loud. Modern utility scale wind turbines like those proposed for PWPP have most of their acoustic energy in the range from under 1 Hz to 500 Hz that is ignored by the dBA calculations. This sound is called infrasound (0-20Hz) and low frequency sound (20-250Hz). Low frequency sounds, including infrasound, are problematic because they propagate much further than higher frequency sound with little loss of energy. That results in people hearing a rumble (very low frequency noise) or roar (low frequency sound above 100Hz) that penetrates their homes, especially at night when the house is quiet. Infra and low frequency sounds are not blocked by normal home construction methods for walls, roofs and windows.

Infra sound is a special case of low frequency sound where the energy has to be very high for the sound to be audible, but some people can “feel” the sound as body vibrations, pressure changes, migraines, tinnitus, dizziness, and other non-auditory effects. This is not limited to wind turbines. It also is a characteristic of helicopter sound emissions or large fans in high rise office buildings when they need maintenance. (In that last case the term is Noise induced Sick Building Syndrome.)

Dr. Schomer’s 2015 paper titled: “A theory to explain some physiological effects of the infrasonic emissions at some wind farm sites” (attached as Exhibit 4) explains how these inaudible levels of wind turbine sound, which are presented as pressure pulsations inside of homes, can trigger these non-auditory sensations and symptoms. The phrase “Wind Turbine Syndrome” was coined by Dr. Nina Pierpont, MD. to describe them. These symptoms cannot be explained as occurring due to audible sound levels in the speech frequency range. See the attached Exhibit 5, which is a one-page summary of wind turbine blade pass frequency and effects, for an explanation of how these pulsations are produced.

Mr. Hessler refers to a study in his written testimony that he participated in for the Wisconsin Public Service Commission for the Shirley Wind Project in Brown County Wisconsin. That study was conducted in the homes of my clients who had filed complaints with the WI PSC during a hearing on a second wind project in another part of the state. The study that Mr. Hessler points to was designed by me for my clients and accepted by the PSC. I developed the test protocol, selected the homes to be tested, and picked the acousticians who would conduct it. Because the complainants were my clients, I did not participate, but was given full access to the data and did an independent analysis for the PSC which confirmed the presence of pulsating infrasound.

This study confirmed that inside the homes, wind turbine pulsations created by the loss of lift on the blades as the blade passes into the wind deficit region in front of the tower was present at levels almost the same as outside the homes. I have attached as Exhibit 6 a set of graphs showing the infrasound that I prepared for the Brown County Health Department showing the infrasound using two types of instrumentation. The graph on the first page shows the spectrograms from multi-hour micro barometer tests in the home with the highest infra sound during the test Mr. Hessler describes. (This was R1 of the study at 3600 feet from the nearest wind turbine). The infrasound pulsations are seen as horizontal bands of energy and are explained in the notes. The last page shows a simultaneous test at R1 and another home located about four (4) miles away where the occupants experience pressure related headaches when the turbines are operating even though none of the wind turbines are visible. The infrasound traces are still present at this distance although somewhat attenuated. It is this ability to propagate long distances that makes the infra sound component of wind turbine noise so problematic.

Brown County's Health Department declared the entire region within 2.5 miles of the Shirley Wind project to be a "Human Health Hazard" zone. This is an official classification under Wisconsin law.

The owners of two of the homes (R1 at 3600 feet and R3 at one mile) abandoned their homes shortly after the project started to operate due to symptoms that included nausea and dizziness. Those homes are still vacant. R2 was abandoned to the mortgage company who resold it to a different family.

Q: Has this study been duplicated?

A: Yes, several times by myself and other acousticians, most notably Steven Cooper of Australia's Acoustics Group. Cooper's Cape Bridgewater study is very detailed and lengthy but can be obtained at http://www.pacifichydro.com.au/english/our-communities/communities/cape-bridgewater-acoustic-study-report/.

He finds that the test subjects in his three test homes were able to reliably sense the starting and stopping of the wind turbines without visual cues. One test subject was functionally deaf due to childhood illness damaging the auditory nerves. This test subject was able to sense the operation of distant wind turbines without any auditory or visual cues. Mr. Hessler refers to this study as one that resulted in him rethinking his position on inaudible infrasound as a source of adverse health effects.

Dr. Schomer references this study in his paper (referenced earlier) and also conducted a peer review of it. His peer review concludes:

> "The results are that there is a cause and effect relationship between turbine power output and subject response, and, at the same time there is no correlation between subject

> response and either sound level or vibration level. These results show that there is a non-visual, non-audible pathway by which wind turbine emissions can cause some specific effects in some people. These results say nothing about the nature of these effects. Nothing internal to the body is discussed. We again reiterate to government and to wind farm operators, if you don't believe the results, replicate the study using clearly independent consultants.
>
> “Some may ask, this is only 6 people, why is it so important? The answer is that up until now windfarm operators have said there are no known cause and effect relations between windfarm emissions and the response of people living in the vicinity of the windfarm other than those related to visual and/or audible stimuli, and these lead to some flicker which is treated, and “some annoyance with noise.” This study proves that there are other pathways that affect some people, at least 6. The windfarm operator simply cannot say there are no known effects and no known people affected. One person affected is a lot more than none; the existence of just one cause-and-effect pathway is a lot more than none. It only takes one example to prove that a broad assertion is not true, and that is the case here. Windfarms will be in the position where they must say: “We may affect some people.” And regulators charged with protecting the health and welfare of the citizenry will not be able to say they know of no adverse effects. Rather, if they choose to support the windfarm, they will do so knowing that they may not be protecting the health and welfare of all the citizenry.”

Q: Has this been duplicated in a controlled laboratory test?

A: Yes. Mr. Hessler references such a study in his testimony. This was reported in a paper presented by Steve Cooper at the Acoustical Society of America’s December 2017 conference and published in the Proceedings of Meetings on Acoustics (POMA) in a paper titled: “Subjective perception of wind turbine noise - The stereo approach.”

Steve Cooper designed a laboratory where he could accurately reproduce the sounds he measured in the Cape Bridgewater homes in both frequency and time domain, down to 3 Hz. He created an audio sample from one of his Cape Bridgewater measurements that reproduced the pulsations at the infrasonic rate of the blade pass frequency. He did blind testing of people who included some who live in wind projects and by others who did not think they were sensitive to such sounds.

Cooper’s controlled experiments reproduced the acoustical characteristics found inside homes where sensitive people have filed complaints of sensations and other non-auditory complaints. Inaudible sound pulsations occurring at infrasonic rates emitted by wind turbines were shown to cause perceptible sensations in test subjects who self-identified as being sensitive to wind turbine infra sound. Those who self-identified as being sensitive to wind turbine infra sound were able to reliably detect when the sample was played or not and could also detect the direction from which the sound came (blindfolded and sitting in a swivel chair). Some of the test subjects who did not identify as "sensitive" were also able to detect the presence of the infra sound pulsations.

Mr. Cooper's study shows that:

1. It is possible to reproduce in a controlled laboratory experiment the acoustic characteristics of wind turbine sound pressure pulsations occurring at infrasonic rates found in homes of people living near utility scale wind turbines who have filed complaints of adverse sensations and health effects.
2. These inaudible acoustic conditions reliably trigger in self-identified "sensitive people" sensations and adverse effects associated with the complaints by people who live in or near the footprint of utility scale wind turbines.

Wind turbine sound emissions consisting of dynamically modulated pressure pulsations at infrasonic rates synchronized to the blade pass frequency were shown to cause sensations and other adverse effects under controlled laboratory conditions.

There are other studies of this type being conducted but they do not use a real audio sample from a home where people have reported the sensations. Those studies rely on what is being called a "surrogate sample" that does not include the dynamically modulated pressure pulsations, they only reproduce the frequency and sound pressure levels measured in the homes. Thus, they do not include the most important characteristic of pulsating noise. These studies report that the test subjects do not respond to the sound. This is a strong piece of evidence that it is the pulsations and not the infra and low frequency sound levels that are important in producing sensations. It also explains why people do not report these sensations when exposed to steady infra sound from the natural environment.

Q: Do you have any comments on the Burns-McDonnell Sound Study for the Prevailing Wind Park Project?

A: Yes. First as indicated by my testimony above I disagree with the idea that a threshold of 45 dBA Leq is protective for people living near the wind project. Second, I reviewed the information on the computer model prepared for the report. I find the model is deficient in many ways. One significant way is that it fails to include two important sets of tolerances. The sound power data used as input to the model is derived using a method that has about a ± 2 dB tolerance for measurement repeatability. This tolerance should have been added to the sound power levels used as input to the model to account for known variability in measurement data. Also, the model uses the formulas and protocols from ISO 9613-2 which states it is not applicable for noise sources that are more than 30 meters above the ground or receiver elevation. Even if the model was appropriate for wind turbine noise the model has known tolerances of ± 3 dBA. This should have also been applied as an adjustment to the Burns-McDonnell sound model. Given these two tolerances the predicted sound levels are as much as 5 dBA low.

Further, the values used for ground attenuation are not disclosed. The proper value for ground attenuation is “0” to turn off any calculations of ground effect. This is because the height of the wind turbines means that the sound emitted by them radiates directly from the blades to the homes without interaction with the ground. The ISO ground attenuation calculations are intended for ground-based noise sources where the sound radiates along a line from source to receiver just above the ground.

Dr. Schomer has in the past, identified additional problems with wind turbine noise prediction using the ISO model methods. He was a member of the committee that developed the ISO 9613-2 standard and its ANSI equivalent (ANSI/ASA S12.62). He has repeatedly stated in hearings and conferences that the model does not properly predict the propagation of low frequency noise. The ISO model range for accuracy is focused on sound in the frequencies that are most important for other types of ground-based community noise sources. In testimony he gave for the White Pines project in Ontario he stated that the model is likely to underestimate the sound propagation from wind turbines by as much as 11 dBA. This is in addition to the issue of tolerances for the calculations. As I have stated above I have also measured wind turbines operating at levels 10 dBA Leq or more above the predicted sound levels.

Q: What does this mean for the Prevailing Wind Park project?

A: It means that the predicted sound levels at receptors in and near the PWPP are <u>at least 5 dBA less</u> than what should be expected if the project was operating and the sounds measured and compared to the model’s predictions. I have conducted such studies and routinely find that the wind turbines exceed the modeled sound levels by 5 dBA and in some cases, especially when the operating mode includes high blade angles or wind turbulence, the model under predicts by 10 or more dBA.

The flaws in the model make it likely that if the project is approved as designed there will be many complaints of annoyance and some of adverse health effects along the lines of what occurred at Shirley Wind and Cape Bridgewater.

Before any decisions are made on permitting this project the applicant should be required to submit a new model that applies the known tolerances to the input data. It should also show the contour lines for 30, 35, and 40 dBA. These new sound levels should then be viewed as indicators of what the community will experience on a day when the wind turbines are operating under optimum conditions for the lowest noise emissions. They are not precision predictions. Review of the model should be done keeping in mind that the operating values can be as much as 10 dB higher than what is predicted, under operating conditions that would be considered normal.

The likely complaint times will be at night when winds at the blades are strong with high wind shears at the hub elevation, but calm or no winds at the ground (called a stable nighttime atmosphere). Studies have shown that these weather conditions occur as frequently as 2 out of 3 nights during warm seasons. Since the ground level winds are calm there is no wind induced noise or leaf rustle to mask the wind turbine noise. This condition is recognized in many jurisdictions (e.g. Ontario) as the “worst-case” condition for complaints.

Q: Do you have any comments on Dr. Roberts' testimony.

A: Yes, however I understand the Dr. Punch will be addressing that testimony in more detail. What I would add is that, in my opinion as an acoustician, Dr. Roberts is not qualified to speak to the issue of acoustics or human response to wind turbine noise. Acoustical engineers are trained in how to measure sound and relate those measurements to human and community response. I saw nothing in his background that qualifies him to speak to these issues.

Dr. Roberts’ testimony is not reliable when read by an experienced acoustician who understands the particular character of wind turbine noise that leads to it being highly annoying at sound levels well below other common community noise sources.

Q: Do you have anything further to add at this time?

A: The foregoing written testimony is to be presented to the South Dakota Public Utilities Commission for SD PUC Docket EL 18-026.

I reserve the right to revise and expand upon these written comments during the hearing.

Richard R. James

Richard R. James

September 10, 2018

Bio Materials for: Richard R. James
Ver: Nov. 8, 2017

Mr. James is the Owner and Principal Consultant for E-Coustic Solutions, LLC, of Okemos, Michigan. He has been a practicing acoustical engineer for over 40 years. He started his career as an acoustical engineer working for the Chevrolet Division of General Motors Corporation in the early 1970s. His clients include many large manufacturing firms, such as, General Motors, Ford, Goodyear Tire & Rubber, and others who have manufacturing facilities where community noise and worker noise exposure occur. In addition, he has worked for many small companies and private individuals. He was actively involved with the Institute of Noise Control Engineers (INCE) since its formation in the early 1970's. He was a full Member from early in the 1990's through 2017.

His academic credentials include a degree in Mechanical Engineering (BME) from General Motors Institute, Flint Michigan (now Kettering Institute). He has been an adjunct Instructor to the Speech and Communication Science Department at Michigan State University from 1985 to 2013 and an adjunct Professor for the Department of Communication Disorders at Central Michigan University from 2012 through 2017. In addition, Mr. James served on the Applied Physics Advisory Board of Kettering Institute from 1997 to 2007.

Specific to wind turbine noise, he has worked for clients in over 60 different communities.

He has provided written and oral testimony in approximately 30 of those cases. He has also authored or co-authored four papers covering wind turbine noise topics including:

- Criteria for wind turbine projects necessary to protect public health (2008),
- Demonstrating that wind turbine sound immissions are predominantly comprised of infra and low frequency sound (2011), and
- A peer reviewed historical review of other types of low frequency noise sources with similar sound emission characteristics, such as large HVAC systems (fans) which caused noise induced Sick Building Syndrome and other noise sources that have known adverse health effects on people exposed to their sound. (2012).
- A peer reviewed literature review of research spanning 40 years showing wind turbines cause risks of adverse health effects from both audible and inaudible sound emissions (2016).

He has been qualified as an expert in acoustics for hearings and court proceedings in several countries. Examples of recent qualifications are:

Jurisdiction	Before	Qualified as:
Ontario, CA (January 2014)	Ministry of Environment (MOE) and Environmental Review Tribunal (ERT)	Qualified to provide evidence on matters related to acoustics and noise control engineering and wind turbines
Alberta, CA (Dec. 2013)	Alberta Utilities Commission (AUC)	An acoustical engineer and acoustician with expertise in the field of sound including noise, low frequency noise, sounds emitted from industrial wind turbines and human response to noise.
Michigan, US	Michigan Circuit Court	1. acoustician with expertise in measurement of wind turbine noise and its effects on people. (Dec. 2013) 2. acoustician qualified to opine that the plaintiff's symptoms were caused by the defendant's wind turbines. After special Daubert Hearing (Dec. 2013)

Revised: Nov. 8, 2017

Computers to quiet the factory

Ever since the Occupational Safety & Health Administration (OSHA) adopted industrial noise standards in 1971, plant engineers have been struggling to reduce the ear-piercing din in factories. But it is a tough job. The hundreds of machines inside a factory produce different sounds, each of which interacts differently with nearby equipment and partitions. Even skilled acoustical engineers often misjudge the effort needed to get down to the noise level the government permits. And because noise control is often expensive, mistakes can be costly.

Now, however, many corporations are turning to computer models to make sure their noise-control efforts will be cost-effective. Spurred by the falling cost of computer time and the high price of noise control, companies are using models to ensure that newly built plants will comply with OSHA noise rules. Managers are also using computers to test whether modifications of an existing plant will actually reduce noise. And executives are finding that models enable them to contest ineffective noise-control measures proposed by the government.


Peter Yates

Engineers James and Van Tifflin: Using models to plan noise control.

The computer's advantage. A noise model is based on equations that state in mathematical form the same laws of physics that consultants have traditionally used to forecast sound levels. These equations predict, for example, the effects of bouncing sound off a wall or absorbing it in acoustical tile. To apply a model to a particular plant, a consultant first measures the several different noises emitted by each machine, then records the size, nature, and placement of noise barriers such as walls and ceilings. When these data are fed into the noise model, engineers can get information about the noise level anywhere in the plant.

Without the computer, a noise consultant must calculate intuitively. The advantage of having a model is in being able to track interactions among a larger number of variables to predict the noise level at each station. A model developed by Total Environmental Systems Inc. in East Lansing, Mich., can cope with 3,500 noise sources and 250 partitions. "There are no more than 10 people in the country who can intuitively evaluate 100 variables," says Richard R. James, TES vice-president.

Many company officials are enthusiastic about the success of these models. Using a computer model developed by TES, General Motors Corp. found that it could slash by 25% its expected use of noise-reducing material in the body-fabricating area of its new Oklahoma City assembly plant. Tests made after the plant was built showed that the model had predicted the actual noise level in the plant to within 2 decibels, a high degree of accuracy. "We can't afford trial and error," notes Woodford L. Van Tifflin, the engineer who oversees GM's noise control system.

Costs. The average machine shop could not afford the $50,000 it cost GM to have TES model a 750,000-sq.-ft. portion of its Oklahoma City plant. The TES prices for less complex jobs start at $18,000. But even clients paying the highest fees say that the savings from modeling more than cover the costs. "Modeling prices are not out of line," argues Robert F. Birdsall, a Ford Motor Co. environmental engineer. Ford recently completed noise modeling for its new Batavia (Ohio) transaxle plant, slated to be in production by the 1981 model year.

Most of the modeling of existing plants is aimed at preventing OSHA citations for excessive noise. But modeling also helps a company fight alleged violations of noise standards. Stanadyne Inc. in Windsor, Conn., recently used a model to show that the government overstated—by a factor of 20—the effectiveness and thus the feasibility of noise control measures that it claimed Stanadyne should have used at its Bellwood (Ill.) plant to keep workers from being exposed to more than 90 decibels. The model's results played a key role in a judge's Dec. 28 decision in favor of the company, claims Stanadyne's attorney, Columbus R. Gangemi Jr. Testimony based on a model "is easier for the court to understand and easier to defend" than traditional expert testimony based on engineering analysis alone, he says.

Saving time. In addition to eliminating the cost of unnecessary or ineffective noise-control measures, modeling husbands executive time. The model can generate a noise map of a new plant using colors and contour lines to indicate the sound level at each worker station. Additional maps then can display the impact of various noise-reduction strategies. So, rather than having to wade through statistical tables or try to follow complex oral explanations, managers can see at a glance what areas in the plant have noise problems and the effect of potential solutions. "It puts complex information into a meaningful summary," says Ford's Birdsall.

Although users of noise modeling are enthusiastic, there is still some skepticism in the acoustical consulting community. These doubts persist despite the widespread use of modeling to cope with other forms of industrial pollution (BW—Oct. 29). "It could be a gimmick," says Paul Jensen, manager of the industrial noise division at Bolt Beranek & Newman, an acoustical consulting firm in Cambridge, Mass. Jensen contends that it is more important to consider the worker. "The problem with the model is that it doesn't say a darn thing about the worker—where he is, how he moves in and out of noisy areas."

Many other consultants, though, contend that Jensen overstates the case against modeling. "We use it successfully for companies having 5 to 1,000 employees," counters Thomas D. Miller, vice-president of Donley, Miller & Nowikas Inc. in East Hanover, N. J. But he cautions that modeling, like any mathematical simulation, is only as valid as the data base and operating assumptions on which it is built. ■

BIOGRAPHICAL SKETCH

NAME	POSITION TITLE	BIRTHDATE
Richard R. James	Principal Consultant, E-Coustic Solutions, LLC (2006-)	3/3/48

ACADEMIC CREDENTIALS

INSTITUTION	DEGREE/POSITION	YEAR	FIELD
General Motors Institute, Flint, MI	B. Mech. Eng.	1966-1971	Noise Control Engineering
Michigan State University, East Lansing, MI	Adjunct Instructor	1985-2013	Acoustics and Effects of Noise on People
Central Michigan University, Mount Pleasant, MI	Adjunct Professor	2012-2017	Wind Turbine Noise and its Impact on People

RESEARCH AND PROFESSIONAL EXPERIENCE:
Richard R. James has been actively involved in the field of noise control since 1969, participating in and supervising research and engineering projects related to control of occupational and community noise in industry. In addition to his technical responsibilities as principal consultant, he has developed noise control engineering and management programs for the automotive, tire manufacturing, and appliance industries. Has performed extensive acoustical testing and development work in a variety of complex environmental noise problems utilizing both classical and computer simulation techniques. In 1975 he co-directed (with Robert R. Anderson) the development of SOUND^{TM}, an interactive acoustical modeling computer software package based on the methods that would be later codified in ISO 9613-2 for pre and post-build noise control design and engineering studies of in-plant and community noise. The software was used on projects with General Motors, Ford Motor Company, The Goodyear Tire & Rubber Co., and a number of other companies for noise control engineering decision making during pre-build design of new facilities and complaint resolution at existing facilities. The SOUND^{TM} computer model was used by Mr. James in numerous community noise projects involving new and existing manufacturing facilities to address questions of land-use compatibility and the effect of noise controls on industrial facility noise emissions. He is also the developer of ONE*dB$^{(tm)}$ software. He was also a co-developer (along with James H. Pyne, Staff Engineer GM AES) of the Organization Structured Sampling method and the Job Function Sound Exposure Profiling Procedure which in combination form the basis for a comprehensive employee risk assessment and sound exposure monitoring process suitable for use by employers regulated by OSHA and other governmental standards for occupational sound exposure. Principal in charge of JAA's partnership with UAW, NIOSH, Ford, and Hawkwa on the HearSaf 2000^{tm} software development CRADA partnership for world-class hearing loss prevention tools.

1966-1970	Co-operative student: General Motors Institute and Chevrolet Flint Metal Fabricating Plant.
1970-1971	GMI thesis titled: "Sound Power Level Analysis, Procedure and Applications". This thesis presented a method for modeling the effects of noise controls in a stamping plant. This method was the basis for SOUNDTM.
1970-1972	Noise Control Engineer-Chevrolet Flint Metal Fabricating Plant. Responsible for developing and implementing a Noise Control and Hearing Conservation Program for the Flint Metal Fabricating Plant. Member of the GM Flint Noise Control Committee which drafted the first standards for community noise, GM's Uniform Sound Survey Procedure, "Buy Quiet" purchasing specification, and guidelines for implementing a Hearing Conservation Program.
1972-1983	Principal Consultant, Total Environmental Systems, Inc.; Lansing, MI. Together with Robert R. Anderson formed a consulting firm specializing in community and industrial noise control.
1973-1974	Consultant to the American Metal Stamping Association and member firms for in-plant and community noise.
1973	Published: "Computer Analysis and Graphic Display of Sound Pressure Level Data For Large Scale Industrial Noise Studies", Proceedings of Noise-Con '73, Washington, D.C.. This was the first paper on use of sound level contour 'maps' to represent sound levels from computer predictions and noise studies.

Nov. 1973	Published: "Isograms Show Sound Level Distribution in Industrial Noise Studies", Sound & Vibration Magazine
1975	Published: "Computer Assisted Acoustical Engineering Techniques", Noise-Expo 1975, Atlanta, GA which advanced the use of computer models and other computer-based tools for acoustical engineers.
1976	Expert Witness for GMC at OSHA Hearings in Washington D.C. regarding changes to the "feasible control" and cost-benefit elements of the OSHA Noise Standard. Feasibility of controls and cost-benefit were studied for the GMC, Fisher Body Stamping Plant, Kalamazoo MI.
1977-1980	Principal Consultant to GMC for the use of SOUND$^{(tm)}$ computer simulation techniques for analysis of design,layout, and acoustical treatment options for interior and exterior noise from a new generation of assembly plants. This study started with the GMAD Oklahoma City Assembly Plant. Results of the study were used to refine noise control design options for the Shreveport, Lake Orion, Bowling Green plants and many others.
1979-1983	Conducted an audit and follow-up for all Goodyear Tire & Rubber Company's European and U.K. facilities for community and in-plant noise.
1981-1985	Section Coordinator/Speaker, Michigan Department Of Public Health, "Health in the Work Place" Conference.
1981	Published: "A Practical Method for Cost-Benefit Analysis of Power Press Noise Control Options", Noise-Expo 1981, Chicago, Illinois
1981	Principal Investigator: Phase III of Organization Resources Counselors (ORC), Washington D.C., Power Press Task Force Study of Mechanical Press Working Operations. Resulted in publishing: "User's Guide for Noise Emission Event Analysis and Control", August 1981
1981-1991	Consultant to General Motors Corporation and Central Foundry Division, Danville Illinois in community noise citation initiated by Illinois EPA for cupola noise emissions. Resulted in a petition to the IEPA to change state-wide community noise standards to account for community response to noise by determining compliance using a one hour $_{Leq}$ instead of a single not-to-exceed limit.
1983	Published: "Noise Emission Event Analysis-An Overview", Noise-Con 1983, Cambridge, MA
1983-2006	Principal Consultant, James, Anderson & Associates, Inc.; Lansing, MI. (JAA), Together with Robert R. Anderson formed a consulting firm specializing in Hearing Conservation, Noise Control Engineering, and Program Management.
1983-2006	Retained by GM Advanced Engineering Staff to assist in the design and management of GM's on-going community noise and in-plant noise programs.
1984-1985	Co-developed the 1985 GM Uniform Plant Sound Survey Procedure and Guidelines with James H. Pyne, Staff Engineer, GM AES.
1985-2013	Adjunct instructor in Michigan State University's Department of Communicative Sciences and Disorders from 1985-2013
1986-1987	Principal Consultant to Chrysler Motors Corporation, Plant Engineering and Environmental Planning Staff. Conducted Noise Control Engineering Audits of all manufacturing and research facilities to identify feasible engineering controls and development of a formal Noise Control Program.
1988-2006	Co-Instructor, General Motors Corporation Sound Survey Procedure (Course 0369)
1990	Developed One*dB$^{(tm)}$, JAA's Occupational Noise Exposure Database manager to support Organizational structured sampling strategy and Job Function Profile (work-task) approach for sound exposure assessment.
1990-1991	Co-developed the 1991 GM Uniform Plant Sound Survey Procedure and Guidelines with James H. Pyne, Staff Engineer, GM AES. Customized One*dB$^{(tm)}$ software to support GM's program.
1990-2006	Principal Consultant to Ford Motor Company to investigate and design documentation and computer data management systems for Hearing Conservation and Noise Control Engineering Programs. This included bi-annual audits of all facilities.
1993-2006	GM and Ford retain James and JAA as First-Tier Partners for all non-product related noise control services.
1993	Invited paper: "An Organization Structured Sound Exposure Risk Assessment Sampling Strategy" at the 1993 AIHCE

1993	Invited paper: "An Organization Structured Sound Exposure Risk Assessment Database" at the Conference on Occupational Exposure Databases, McLean, VA sponsored by ACGIH
1994-2001	Instructor for AIHA Professional Development Course, "Occupational Noise Exposure Assessment"
1996	Task Based Survey Procedure (used in One*dB$^{(tm)}$) codified as part of ANSI S12.19 Occ. Noise Measurement
1995-2001	Coordinate JAA's role in HearSaf 2000^{tm} CRADA with NIOSH, UAW, Ford, and HAWKWA
1997-2007	Board Member, Applied Physics Advisory Board, Kettering Institute, Flint, Michigan
2000	Use of structured, interactive interviews in retrospective noise exposure assessment in an occupational epidemiologic study, Prince, Waters, Anderson, and James, JASA,, April 2000
2002-2006	Member American National Standards Institute (ANSI) Accredited Standards Committee S12, Noise
2006	Closed James, Anderson and Associates, Inc. (JAA) and founded E-Coustic Solutions (E-CS)
2006-Present	Consultant to local communities and citizen's groups on proper siting of Industrial Wind Turbines. This includes presentations to local governmental bodies, assistance in writing noise standards, and formal testimony at zoning board hearings and litigation.
2008	Paper on "Simple guidelines for siting wind turbines to prevent health risks" for INCE Noise-Con 2008, co-authored with George Kamperman, INCE Bd. Cert. Emeritus, Kamperman Associates.
2008	Expanded manuscript supporting Noise-Con 2008 paper titled: "The "How To" Guide To Siting Wind Turbines To Prevent Health Risks From Sound"
2009	"Guidelines for Selecting Wind Turbine Sites," Kamperman and James, Published in the September 2009 issue of Sound and Vibration.
2010	Punch, J., James, R., Pabst, D., "Wind Turbine Noise, What Audiologists should know," Audiology Today, July-August 2010
2011	Jerry L. Punch, Jill L. Elfenbein, and Richard R. James, "Targeting Hearing Health Messages for Users of Personal Listening Devices," Am J Audiol 0: 1059-0889_2011_10-0039v1
2011	Bray, W., HEAD Acoustics, James, R., "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," invited paper for Noise-Con 2011, Portland OR
2012	James, R., "Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard," April 2012, Bulletin of Science, Technology and Society
2012	Appointed to position as Adjunct Professor in the Department of Communication Disorders at Central Michigan University.
2014	Negative Health Effects of Noise from Industrial Wind Turbines-Parts 1-3, Punch, J, James, R., Hearing Health Technology Matters, http://hearinghealthmatters.org/hearingviews/2014/wind-turbine-noise-evidence-health-problems/
2016	Punch, J. L., James, R.R., "Wind turbine noise and human health: a four-decade history of evidence that wind turbines pose risks," Journal of Hearing Health and Technology Matters, October 4, 2016, http://hearinghealthmatters.org/journalresearchposters/files/2016/09/Final-Final-16-09-30-Wind-Turbine-Noise-Final-Manuscript-HHTM-Punch-James.pdf.

Professional Affiliations/Memberships/Appointments

Research Fellow - Metrosonics, Inc.	American Industrial Hygiene Association (through 2006)
National Hearing Conservation Association (through 2006)	Institute of Noise Control Engineers (Member through 2017)
American National Standards Institute (ANSI) S12 Working Group (through 2006)	Founder and Board Member of the Society for Wind Vigilance, Inc.
Adjunct Professor, CMU 2012-2017	Adjunct Instructor, MSU 1985-2013

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List of Recent Publications

Sept. 5, 2017

2000	JASA, April 2000, Prince, Waters, Anderson, and James, Use of structured, interactive interviews in retrospective noise exposure assessment in an occupational epidemiologic study
2008	Paper on guidelines for siting wind turbines to prevent health risks for INCE Noise-Con 2008, co-authored with George Kamperman, Kamperman Associates.
2008	Expanded manuscript supporting Noise-Con 2008 paper titled: "The 'How To' Guide To Siting Wind Turbines To Prevent Health Risks From Sound"
2009	"Guidelines for Selecting Wind Turbine Sites," Kamperman and James, Published in the September 2009 issue of Sound and Vibration.
2010	Punch, J., James, R., Pabst, D., "Wind Turbine Noise, What Audiologists should know," Audiology Today, July-August 2010
2011	Jerry L. Punch, Jill L. Elfenbein, and Richard R. James , "Targeting Hearing Health Messages for Users of Personal Listening Devices," Am J Audiol 0: 1059-0889_2011_10-0039v1
2011	Bray, W., HEAD Acoustics, James, R., "Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception," invited paper for Noise-Con 2011, Portland OR
2012	James, R., "Wind Turbine Infra and Low Frequency Sound: Warning Signs that were not Heard," April 2012, Bulletin of Science, Technology and Society, http://bsts.sagepub.com, DOI:10.1177/0270467611421845
2014	Negative Health Effects of Noise from Industrial Wind Turbines-Parta 1-3, Punch, J, James, R., Hearing Health Technology Matters, http://hearinghealthmatters.org/hearingviews/2014/wind-turbine-noise-evidence-health-problems/
2016	Punch, J. L., James, R.R., "Wind turbine noise and human health: a four-decade history of evidence that wind turbines pose risks," Journal of Hearing Health and Technology Matters, October 4, 2016, http://hearinghealthmatters.org/journalresearchposters/files/2016/09/16-10-21-Wind-Turbine-Noise-Post-Publication-Manuscript-HHTM-Punch-James.pdf.

Published in the
Encyclopedia of Environmental Management (peer review panel for all articles).
See Appendix A for proposed criteria

Noise: Windfarms

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Massey University, New Zealand

Abstract
Windfarms consist of clusters of wind turbines, which, when placed in populated areas, are associated with intrusive and unwanted sound. A relatively new noise source; wind turbine noise has characteristics sufficiently different from other, more extensively studied, noise sources to suggest that preexisting noise standards are not appropriate. Though research into the human impacts of wind turbine noise has appeared only in the last decade and in small quantity, the data suggest that, for equivalent exposures, wind turbine noise is more annoying than road or aviation noise. Furthermore, the particular characteristics of wind turbine noise may be likely to cause sleep disruption. As with other impulsive noise sources, time-aggregated noise metrics have limited utility in protecting public health, and a cluster of metrics should be used in order to estimate potential threat. At this time, however, the quantity and quality of research are insufficient to effectively describe the relationship between wind turbine noise and health, and so legislation should apply the precautionary principle or conservative criteria when assessing proposed windfarm developments.

INTRODUCTION

Planning authorities, environmental agencies, and policy makers in many parts of the world are seeking information on possible links between wind turbine noise and health in order to legislate permissible noise levels or setback distances. Concurrently, larger and noisier wind turbines are emerging, and consent is being sought for progressively larger windfarms to be placed even closer to human habitats. While noise standards can effectively and fairly facilitate decision-making processes if developed properly, the current standards on offer suffer severe conceptual difficulties. Specifically, noise metrics considered by many in the industry as best practice may in fact relate little to health outcome variables such as annoyance or sleep disruption. In this entry, we describe the physical characteristics of wind turbine noise, review the impact of such noise on humans, and critique current approaches to mitigation.

INDUSTRIAL WIND TURBINES

Industrial wind turbines transform kinetic energy from the wind into electricity, a practice dating back over 100 years. Structurally, wind turbines can be decomposed into three key components (Fig. 1). First, wind turbines possess a rotor, consisting of one or more blades designed to rotate when exposed to wind. The rotor can be thought of as a type of sail, catching wind in order to induce movement. Depending on the axis of blade rotation, wind turbines can be categorized as either horizontal-axis (the most common) or vertical-axis turbines. The second major component is the generator or "dynamo." The generator component includes a gearbox to regulate the speed of the dynamo and components to change blade pitch and plane of rotation with respect to wind direction. The dynamo can be used as a motor to maintain rotation at very low wind speeds. Third, there is a tower supporting the rotor and, typically, the generator. The size of a wind turbine can be specified either as a dimension (e.g., tower height measured from the ground to the top of a blade at its highest point) or as an electrical output (e.g., watts). Currently, turbines range from approximately 2 to 200 m high and from approximately 50 W to 6 MW.

Wind turbines can be erected in isolation or in sets and be located either onshore (i.e., terrestrial) or offshore (i.e., marine), though the latter is associated with higher construction costs. Industrial-scale wind energy generation, involving the saturation of an optimum number of wind turbines in a fixed area of land, gives rise to the concept of the "windfarm" or "wind park." Wind energy developers seek areas that have good consistent wind flow and close access to energy grids. The proliferation in the number of windfarms established globally in the past decade has been largely driven by environmental concerns such as climate change, renewableness and sustainability, and strategic energy considerations relating to the depletion of fossil fuels.[1] However, in the absence of large-scale electricity

Encyclopedia of Environmental Management DOI: 10.1081/E-EEM-120047802

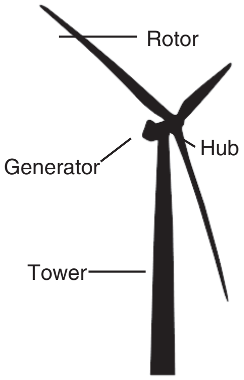

Fig. 1 Components of a typical horizontal-axis wind turbine.

storage devices (i.e., batteries), the contribution of wind energy to a nation's electricity needs is likely to be peripheral. Another barrier is social acceptance, with reviewed social surveys indicating citizens supporting renewable energy in principle but opposed to having windfarms in their immediate vicinity due to visual impacts on the landscape, shadowflicker from the blades, and fears of noise-induced annoyance and sleep disruption.

ACOUSTIC PROFILE OF WIND TURBINE NOISE

The sound generated from a windfarm is qualitatively different from any sound source commonly met in the environment, can rapidly switch from being stationary to nonstationary, and can vary by as much as 20 dB within a single minute. When it interferes with human activities, wind turbine sound becomes a type of noise. Analysis of windfarm noise poses distinct challenges, including the identification of acoustic energy that can be directly attributed to the turbines and the detection of special audible characteristics, including distinct tonal complexes and modulation effects. Windfarm noise is often a broadband low-amplitude noise constantly shifting in character ("waves on beach," "rumble-thump," "plane never landing." etc.). In this respect, windfarm noise is not like, for example, traffic noise or the continuous hum from plant and machinery. When assessed, wind turbine noise is often related to either wind speed (m/s) or electrical output (watts) and typically increases with both.

When the wind reaches a blade, it flows both over and under the blade. The part of the airflow with momentum great enough to break away forms trailing vortexes and turbulence behind the blade, producing a set of sound sources. The power of each sound source depends on the strength of the turbulence, which in turn depends on the speed of airflow; the compressibility and viscosity of the air; the design and surface texture (roughness) of the blade; the wind speed; and the velocity of the blade at that point. The faster the blade rotates, the earlier the breakup in the boundary vortexes and the greater the interaction between the vortexes emanating by adjacent wind turbines. An amplification of potential noise occurs when two or more turbines are, or nearly are, synchronous, such that the blade passing pulses coincide and then go out of phase again.[2] With exact synchronicity, there is a fixed interference pattern; with near synchronicity, concurrent arrival of pulses will change over time and place.

Noise emissions from modern wind turbines are primarily due to turbulent flow and trailing edge sound, blade characteristics, blade/tower interaction, and to a lesser degree, mechanical processes. The most commonly used description of wind turbine noise is the A-weighted

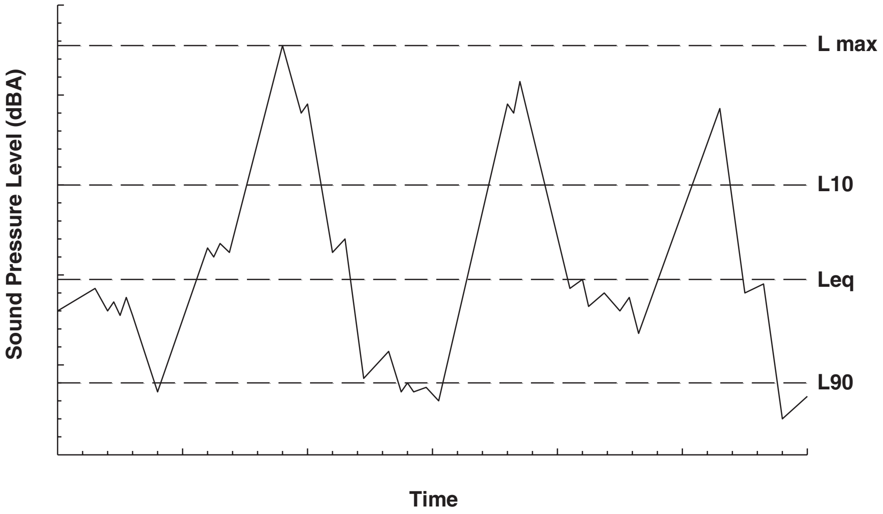

Fig. 2 Chart illustrating different noise descriptors. L10 is the level exceeded 10% of the time, while L90 is the level exceeded 90% of the time. The time-average (equivalent continuous) sound pressure level, Leq, represents the average acoustic energy across a defined measurement epoch.

sound pressure level, which is expressed in decibels (notated dBA). The most commonly used noise compliance assessment methods for windfarms involve the "time-average" sound level L_{Aeq} or the background sound level L_{A90}. These levels are quite different as the time-averaged ambient sound level includes all noises from near and far. The difference between these levels, and other common levels, is illustrated in Fig. 2. The chart shows that sound levels change over time and that any derived sound level index is a summary of fluctuating levels in that time period. In a relatively short time period, such as 10 minutes, the unique noise events such as bangs or thuds from turbines shifting in the wind may be captured. If the time period is relatively long, for example, an hour, then evidence of unique short-term noise events is reduced because the sound energy is "averaged" over the whole hour, and the single-value A-weighted level will not represent short-term variations in sound character. If extraneous noise (e.g., insect noise) is included in the wind turbine measurement, its contribution to the overall level must be determined, though how this is undertaken remains a challenge.[3]

The A-frequency–weighted sound pressure level or "sound level" is the most common sound descriptor and is reputedly analogous to our hearing at medium sound levels. This is not strictly true, and the A-weighting has a significant restriction in that it does not permit measurement or assessment of low-frequency sound (i.e., 20 to 250 Hz). For more complex situations where dominant tonal components are significant (i.e., special audible characteristics), a procedure for determining tonal adjustment requiring one-third octave band frequency or narrow-band analysis is needed. These assessment procedures require the "C" weighting for low frequency or the unweighted (also known as "Z") response to measure both low-frequency and infrasonic sound. Whereas the dBC metric is able to include low-frequency sounds such as the audible rumble and thump from wind turbines, the dBZ response is more suitable for infrasound measurements (i.e., typically inaudible energy below 20 Hz). Fig. 3 presents a third octave band analysis of outdoor wind turbine noise recorded over a 6-hr period. Other measures include assessments for tonality or low-frequency sound referenced to third octave bands and the "G" weighting for infrasound. Aside from physical measures of amplitude (e.g., dBA), wind turbine noise can be quantified with a variety of other acoustical and objective psychoacoustic measures, including amplitude modulation (for example, 100 msec samples of peak, time-average, or fast response), sound quality (including audibility, dissonance, roughness, fluctuation strength, sharpness, tonality), loudness (for steady, time-varying, and impulsive sounds), and unbiased annoyance.[4]

Certification of wind turbine noise is undertaken in accordance with the International Standard IEC 61400-11:2002.[5] Emission levels are to be reported as A-weighted time-averaged (L_{Aeq}) sound levels in one-third octave bands. Audibility is calculated by reference to tones. An informative chapter in IEC 61400-11 states the following: "In addition to those characteristics of wind turbine noise described in the main text, this emission may also possess some, or all of the following: infrasound; lowfrequency noise; impulsivity; low-frequency modulation of broad band or tonal noise; other, such as a whine, hiss, screech, or hum, etc., distinct pulses in the noise, such as bangs, clatters, clicks or thumps, etc." Unfortunately, many of these parameters are not reported by the turbine manufacturer and cannot be predicted with the simple

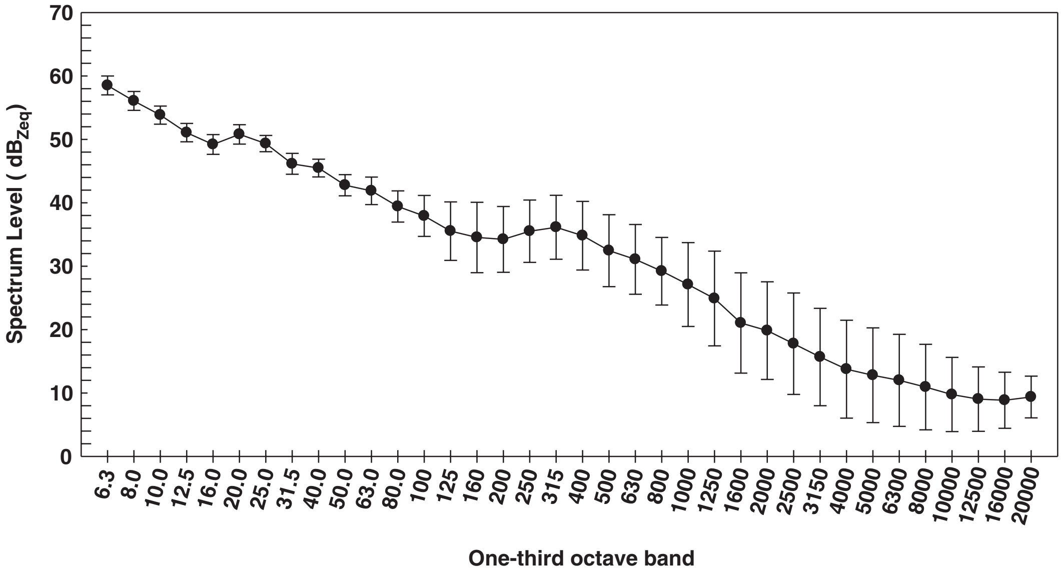

Fig. 3 One-third octave band analysis of time-average unweighted sound pressurelevel (dB_{Zeq}) for wind turbine sound measured from 7:00 PM to 1:00 AM outside of a residence.

Table 1 Factors affecting the prediction of wind farm noise levels at a receiver.[a]

- The true sound power level of the turbine(s) at the specified wind speed
- The reduction in sound level due to ground effects
- The increase or reduction in sound level due to atmospheric (meteorological) variations and wind direction
- The variation due to modulation effects from wind velocity gradient
- Increase and reduction in sound levels due to wake and turbulence modulation effects due to turbine placement and wind direction
- Increased sound levels due to synchronicity effects of turbines in phase due to turbine placement and wind direction
- Building resonance effects for residents inside a dwelling

[a]A conservative set of noise predictions should take all factors into account.

calculation methods currently available. The prediction of windfarm sound levels is most often referenced to national or international standards that have been based on ISO 9613-2.[6] The propagation method is calculated with the receivers being downwind from the noise source(s). All prediction models have uncertainty to their accuracy of prediction. Table 5 of the ISO 9613-2 standard gives an estimated accuracy for broadband noise of ±3 dB at between 100 and 1000 m. This is due to the inherent nature of the calculation algorithms that go into the design of the model, the assumptions made in the implementation of the model, and the availability of good source sound power data. The ISO 9613-2 method holds for wind speeds of between approximately 1 and 5 m/s, measured at a height of 3 to 11 m above the ground. However, wind turbines are sound sources that operate at higher wind speeds than allowed for under the standard, and an accuracy of ±7 dB can be expected.[3] Ultimately, the received noise levels at residences will vary subject to varying meteorological conditions in the locality (e.g., wind speed and direction, wind shear, temperature, humidity, inversions), among other factors (see Table 1), all of which must be accounted for when measuring or modeling wind turbine noise levels.

THE HUMAN IMPACTS OF WIND TURBINE NOISE

A Psychological Description of Wind Turbine Noise

At the psychological level of description, wind turbine noise is most frequently characterized as a swishing or lashing sound or less commonly as thump/throb, low-frequency rumble, or a rustling sound.[7,8] Wind turbines produce noise with an impulsive character[9] and while the actual cause of the swishing or thumping has not yet been fully elucidated, it has been demonstrated that the swishing or thumping pattern is common with larger turbines[10] and may result from a fluctuating angle of attack between the trailing edge of the rotor blade and wind, or wind speed inequalities across the area being swept by the rotor blades.[11] It is thought that the swishing sound may be linked to activity in the 2000 to 4000 Hz band, with the pace of the rotor blades determining the degree of amplitude modulation.[12] Unfortunately, such amplitude-modulated sounds are generally attenuated poorly by background noise, especially so in rural areas.[13] Further, because human sensory systems behave as contrast analyzers, fluctuations in the incoming stimulus field tend to direct attention and so are more easily detected. Thus, amplitude-modulated sounds such as wind turbine noise are readily perceived and difficult to filter out, making them especially intrusive.[14] The loudness of a wind turbine depends on a number of factors, including wind speed, sound-attenuating materials between the turbines and the receiver, other masking sounds, the season, and time of day. The loudness of a modern 2 to 3 MW wind turbine can be compared to a car on a motorway, autobahn, or freeway,[15] with a sound power level of 94 to 104 dBA at a windspeed of 8 m/s.[16] Wind turbine noise is perceived louder at night and during the summer months and when the wind is blowing from the direction of the turbines toward the receiver.[7,8]

Quantifying the Health Impacts of Wind Turbine Noise

Elucidating a causal mechanism between an environmental event and health is a complicated undertaking, and noise effects are commonly “indirect” as opposed to “direct.” According to the biomedical model of health (Fig. 4a), a direct health effect implies a direct pathological relationship between an environmental parameter (e.g., noise level) and a target organ. An alternative approach (Fig. 4b) distinguishes between direct health effects and psychosomatic illness, the latter indicting that any physiological illness coinciding with the onset of wind turbine noise is caused by a negative psychological response to the noise and not the noise *per se*. Thus, anxiety or anger in the presence of wind turbine noise induces stress and strain that, if maintained, can eventually lead to adverse health effects. A counter argument to this approach is that some individuals are simply more susceptible to noise than other individuals, which fits with the general concept of biological and physical variation. In the field of epidemiology, the differential susceptibilities of individuals are known as risk factors or vulnerabilities, with noise sensitivity being one risk factor related to negative responses to intrusive noise. A second challenge to the psychosomatic approach comes from documented instances of individuals who initially welcomed wind turbines into the community but who later campaigned to have them removed due to undesirable noise exposure.[17] Lastly, the veracity of psy-

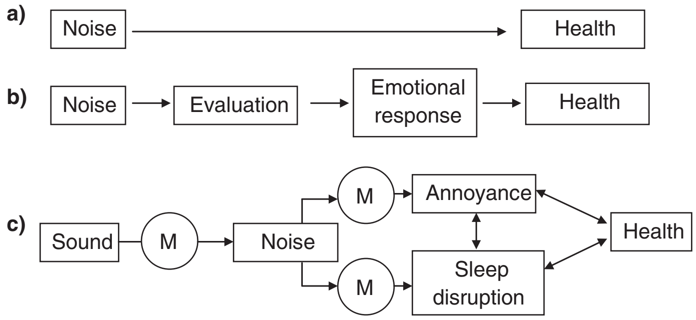

Fig. 4 Three models representing the relationship between noise and health: the biomedical model (a) stipulating a direct causal relationship and indirect models (b and c) containing moderators and mediators.

chosomatic arguments lessens in the face of feasible biological mechanisms describing the relationship between health and noise.[18]

An alternative and more accepted approach would be to adopt the World Health Organization's (WHO's) definition of health:[19] "A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity." The forerunner of the biopsychosocial model, the WHO's definition states that optimal human functioning is determined by the interplay of biological, environmental, psychological, and social factors. Fig. 4c displays a model consistent with the WHO's approach, in which the impact of noise is moderated by environmental, psychological, and social factors. A context-relevant model proposed by van den Berg and colleagues,[8] based on previous wind turbine literature, takes a similar shape to that presented in Fig. 4c. They dichotomize moderators (denoted "M" in Fig. 4c) into environmental moderators (e.g., degree of urbanization, house type, and ambient sound level) or psychological and demographic moderators (e.g., age, gender, education, employment status, attitudes to wind energy, noise sensitivity, and whether the individual receives a monetary return from the turbines). Other models linking wind turbine sound and health have been proposed[20] but can be considered extensions of that presented in Fig. 4c.

As a new source of noise, the impact of wind turbine noise is understandably understudied relative to aviation and road traffic noise. Consequently, little data exist with which to assess the impacts of wind turbine noise on health, a state of affairs compounded by rapid development of wind turbine technology, in which data collected for smaller and less powerful turbines are not generalizable to larger, more modern turbines.[9,21] To date, there have been two approaches to collecting wind turbine noise impact data, either epidemiological studies relying on masked surveys or direct clinical case studies.[22] Both approaches typically focus on the emotional impacts of noise (i.e., annoyance), upon sleep disruption, and/or the degradation of well-being and increases in stress that arise from sleep disturbance and annoyance. Irrespective of approach, however, case studies,[23–25] and epidemiological studies[7,8,20] have provided evidence that, like road traffic and aviation noise, wind turbine noise can be associated with negative health outcomes.

Wind Turbine Noise and Annoyance

People generally respond more negatively to man-made noise than to natural sounds,[26] and this generalization holds true for wind turbine noise.[16] From a psychological perspective, chronic exposure to community noise can impact health through information overload, overarousal, loss of coping strategies, loss of privacy, and loss of perceived control. These mechanisms give rise to a number of subjective responses to noise, of which the most common is annoyance. As a psychological stressor,[27] noise annoyance can express itself through malaise, fear, threat, uncertainty, restricted liberty, excitability, or defenselessness.[28] Furthermore, annoyance may be accompanied by intense anger, especially if one believes that they are being harmed unnecessarily. Thus, the term "annoyance" is often misinterpreted by the layperson as a feeling brought about by the presence of a minor irritant. The medical usage, in contrast, exists as a precise technical term and defines annoyance as a mental state capable of degrading health and well-being,[29,30] and it is classified as an adverse health effect by the WHO.[31]

There have been few studies estimating the health impacts of windfarms, with a series of studies undertaken in Scandinavia contributing the most to current knowledge. A seminal Swedish study undertaken by Pedersen and Persson Waye[7] sought to document the prevalence of wind turbine–induced annoyance and, further, to generate dose–response relationships between the two. Respondents were located between 150 and 1200 metres from the nearest wind turbine and were classified into noise exposure categories (see Fig. 5). A significant relationship between dose (dBA) and annoyance was reported, but the variability in annoyance scores explained by noise level was small (adjusted $R^2 = 0.13$). Those reporting annoyance indicated a daily or nearly-everyday intrusion of windfarm noise. Those describing the noise as "swishing" were more

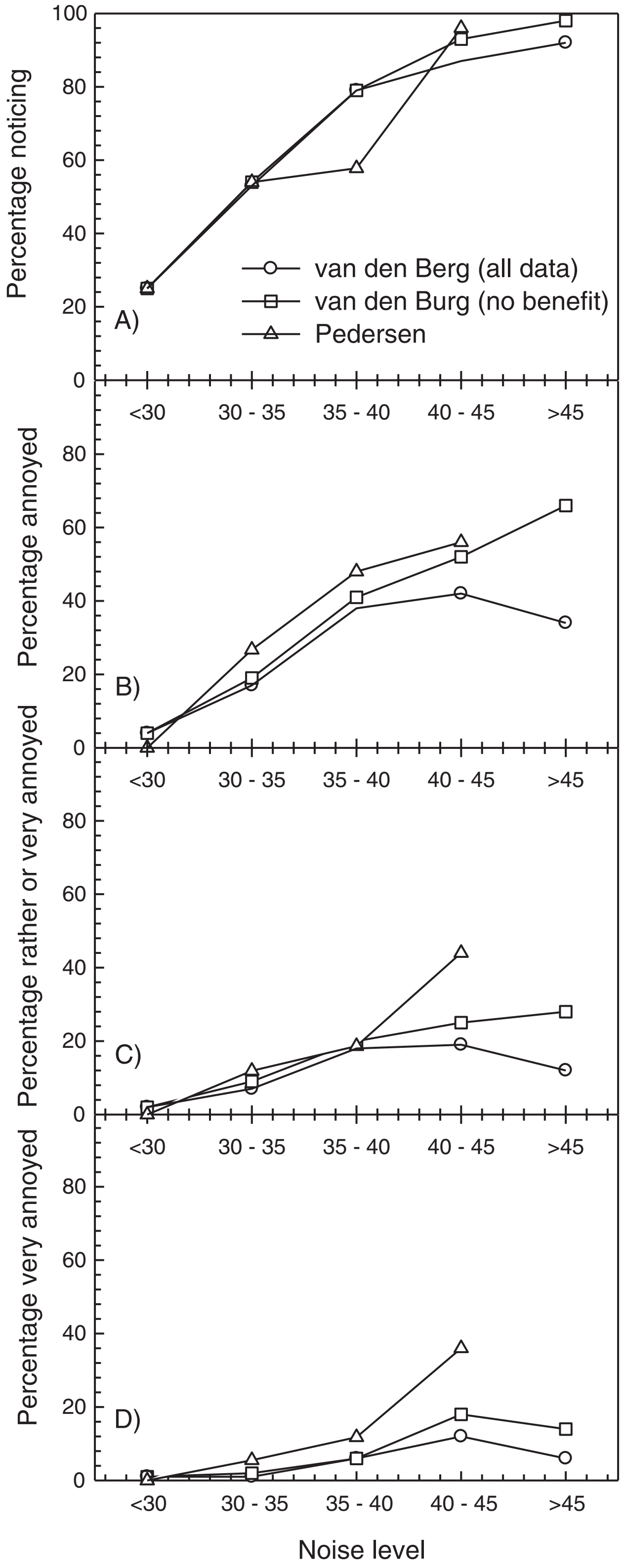

Fig. 5 Perception of wind turbine noise as a function of noise level for three sets of data:Tables 7.25 (complete data set) and 7.26 (no economic benefit of turbines) from van den Berg et al.[8] and Pedersen and Persson Waye's[7] Table V. Plot A is percentage noticing the noise, while plots B to D are for annoyance. Plot B includes data from plots C and D, and plot C includes data from plot D.

likely to report noise annoyance, a finding replicated in a subsequent study reporting a high correlation ($r = 0.664$) between the swishing sound and annoyance.[14] Among those who noticed the noise, 11.2% reported being annoyed when indoors. A small but significant correlation was found between noise annoyance and noise sensitivity, with approximately 50% of the rural-dwelling respondents describing themselves as noise sensitive. Those making negative appraisals of the wind turbines, for example, as visually incongruent with the landscape, were at higher risk of an annoyance response. On the basis of their data, the authors undertook follow-up studies[14–16,22] supporting their conclusion that wind turbine noise maybe more potent than other categories of environmental noise (e.g., road or aviation) and appealed for further studies to determine why this might be. In a later report, Pedersen[22] suggests that coping strategy may moderate the relationship between wind turbine noise and stress.

Van den Berg et al.[8]analyzed data from 725 Dutch nationals residing within 2.1 km of a wind turbine and who were exposed to calculated outdoor noise levels between 24 and 54 dB(A). Approximately 60% of the sample could hear the turbines outdoors, while 33% reported that they could hear the wind turbines indoors. Of the 45% ($n = 231$) who noticed the sound of the rotor blades, 24.7% were not annoyed, 25.8% were slightly annoyed, 19.5% were rather annoyed, and 29.9% were very annoyed. The sound level explained approximately 25% of the variability in annoyance scores, and those who compared the noise to an amplitude modulation (i.e., swishing or lashing) were more likely to be annoyed, though this is not a novel finding.[14,32,33] Fig. 5 plots the data from van den Berg et al., presenting proportions of detection and elicited annoyance as a function of noise level, for their entire dataset (Fig. 5, circles) and for those receiving no economic benefit (Fig. 5, squares). Note that, for those receiving no economic benefit, a monotonic relationship is evident, while a non-monotonic function occurs when individuals benefiting financially from the turbines are included. Van den Berg[8] reports that this depreciation in annoyance of those benefiting economically can be explained by the control they have over the wind turbines, such that they can impede their operation if noise levels increase. Finally, it was reported that annoyance was positively correlated with stress scores, though a causal relationship could not be inferred.

It is accepted that both the physical parameters of the noise and the psychological characteristics of the listener combine to produce noise annoyance.[34] On the physical side, the relatively high annoyance levels elicited by wind turbine noises (e.g., swishing or thumping) may be explained by the increased fluctuation of the sound, up to 4 to 6 dB for a single turbine operating in a stable atmosphere.[11] Individuals are also highly sensitive to changes in frequency modulation variations of approximately 4 Hz or greater.[4] Noting that amplitude-modulated sound is known to be more annoying than unmodulated sound, Lee et al.,[34] in a laboratory setting, demonstrated that amplitude-modulated wind turbine noise was consistently judged to be more annoying than its unmodulated counterpart. Thus, the dominant acoustic driver of annoyance is likely to be noise dynamics rather than noise level. Other physical parameters linked to annoyance include terrain complexity, with rural terrain associated with greater annoyance than urban areas, possibility due to more complicated terrain exhibiting various focusing or defocusing effects and greater ground reflection.

While there is a strong correlation between the sound pressure level (i.e., amplitude) of a sound wave and the perceived loudness of a sound, there is no one-to-one mapping between sound pressure level and the psychological responses that individuals have to a sound.[35] Many non-acoustical factors determine how annoyed one will become toward a source of noise.[36–38] Thus, the response of the individual to the sound is just as important as the parameters of the acoustic wave, and the "people" side of noise should not be omitted from acoustical reports. Table 2 lists, in no particular order, non-acoustical factors found to influence levels of noise annoyance.[39] In relation to windfarms, the personal factors listed in Table 2 have been found to strongly influence how exposed individuals perceive the noise.[16] In addition, perceptions of amenity, individuals seeking refuge from urban noise, or the lower ambient sound levels typical of the rural environment may explain why annoyance responses are higher in rural as opposed to urban settings.[13,16]

When considering wind turbine noise and annoyance data emerging from the literature, a number of risk factors are evident, including an effect of age and educational status but not gender.[8] Employment status was also linked to wind turbine noise–induced annoyance in one study, possibly due to impeded restoration,[16] but to date, there are no data meaningfully comparing ethnicity or national groups (but see Pedersen et al.[40]). The general public view wind turbines as necessary but ugly,[14] and it is possible that the visual impact of a windfarm can interact with noise level to cause moderate annoyance. This amplification of annoyance is possibly due to a violation of the landscape–soundscape continuum constructed by those who choose to live in areas that later contain windfarms,[41] or alternatively, multisensory engagement may enhance detection and identification of wind turbine noise.[42] The degree of influence of the visual aspects of windfarms has yet to be determined, with laboratory studies suggesting that it is wind turbine noise and not the visual impact that underlies the annoyance response,[41] while epidemiological studies suggest that the visual effects are nontrivial. [40]

Table 2 Non-acoustical factors influencing the degree of annoyance to noise.

- Perceived predictability of the noise level changing
- Perceived control, either by the individual or others
- Trust and recognition of those managing the noise source
- Voice, the extent to which concerns are listened to
- General attitudes, fear of accidents, and awareness of benefits
- Personal benefits, how one benefits from the noise source
- Compensation, how one is compensated due to noise exposure
- Noise sensitivity
- Home ownership, concern about plummeting house values
- Accessibility to information relating to the noise source

Source: From Flin dell and Stallen.[39]

Wind Turbine Noise and Sleep

The deleterious effects of noise on sleep and the consequences of sleep loss are well documented and are a major concern for governments.[43] In comparison with road, rail, and aircraft noise, there is little research on the effects of wind turbine noise on sleep. However, there is no doubt that wind turbine noise can and does disturb the sleep of those living nearby. Sleep disruption is the predominant symptom in the thousands of anecdotal cases reported in the press and on the Internet and is confirmed by more structured surveys.[25] The quantity, consistency, and ubiquity of complaints has been taken as *prima facie* epidemiological evidence of a causal link between wind turbine noise, sleep disruption, and ill health.[44]

Early investigations into wind turbine noise and sleep are difficult to interpret as researchers used imprecise outcome measures, generally relying on recalled sleep disturbances such as difficulty in initiating or returning to sleep, which tends to underestimate the magnitude of the noise impact and its consequences.[45] One of the earliest studies ($n = 128$) reported that approximately 16% of respondents living at calculated outdoor turbine noise exposures exceeding 35 dB L_{Aeq} stated that wind turbine noise disturbed their sleep.[7] A New Zealand study of 604 households within 3.5 km of a windfarm found that 42 reported occasional and 26 frequent sleep disturbance.[46] The largest wind turbine noise study to date, "Project WINDFARMperception,"[8] concluded that turbine noise was more of an annoyance at night and that interrupted sleep and difficulty in returning to sleep increased with both indoor and outdoor calculated noise levels. Even at the lowest noise levels, 20% of 725 respondents reported disturbed sleep at least one night per month. In a meta-analysis[40,47] of three European datasets ($n = 1764$),[7,8,16] there was a clear increase in levels of sleep disturbance with dB L_{Aeq} in two of the three studies. In one study, an increment in self-report sleep disturbance occurred between 35 and 40 dBA, while in the other, it occurred between 40 and 45 dBA.

More recent research into wind turbine noise and sleep includes two studies reported by Nissenbaum, Aramini, and Hanning.[48] In the first, a pilot study, a structured questionnaire was administered to 22 subjects living 370 to 1100 m from twenty-eight 1.5mW turbines and a control group ($n = 28$) living at least 4.5 km from the nearest turbine. The study group had clinically and statistically worse sleep disturbance, headache, vestibular symptoms, and psychiatric symptomatology. The second study, using validated questionnaires, administered the Pittsburgh Sleep Quality Index (PSQI), Epworth Sleepiness Score (ESS), and Short-form health survey (SF36) to 79 subjects living between 375 and 6600 m from two windfarms. Those living within 375–1400 m reported worse sleep, were sleepier, and had worse SF36 mental summary scores than those between 3 and 6.6 km from a turbine. Psychiatric symptom scores (irritability, stress, anger, hopelessness, and anxiety) were significantly greater, as was a composite mental health score. They were also more likely to report headaches, nausea (31.6% vs. 12.2%), and a willingness to move away. Modeled dose–response curves of both sleep and health scores against distance from nearest turbine (Fig. 6a–c) were significantly related after controlling for gender, age, and household clustering. There was a sharp increase in effects between 1 and 2 km. This study is the first to use appropriate sleep outcome measures[45] and to use a control group. While the sample size is modest (*n* = 78), it is convincing evidence that wind turbine noise adversely affects sleep and health for those living within 1.5 km of turbines.

Mechanisms explaining the effects of wind turbine noise on sleep have been considered, but would benefit from further empirical support.[45] Noise of any description can interfere with sleep by preventing the onset of sleep either at sleep initiation or at the return to sleep after a spontaneous or induced awakening. The amplitude, character, and associations of the noise are all important as is the noise sensitivity of the individual and the psychological response to the noise. In this respect, wind turbine noise seems to be particularly annoying, possessing an impulsive nature with short bursts of low-frequency sound, making it audible 10–15 dBA below background level.[38,49] Nocturnal atmospheric stability ensures that wind turbine noise is maintained while ground level ambient noise diminishes. Indoor noise levels for most noise sources can be reduced by closing windows; however, the low-frequency content of wind turbine noise means that it may be more audible indoors than outdoors. Additionally, during warmer months, windows are more likely to stay open to control thermal parameters, whence the inability to control or modify wind turbine noise will contribute to the annoyance and, presumably, the effect on sleep onset.[16]

Noise may also cause awakenings and arousals. Arousal is a brief lightening of sleep that is not recalled. Sleep becomes fragmented and, if enough arousals occur, induces the same consequences as reduction of total sleep time. Awakenings are arousals of sufficient degree for wakefulness to be reached and long enough (greater than 10 sec) to be recalled. Arousals are more likely than awakenings,

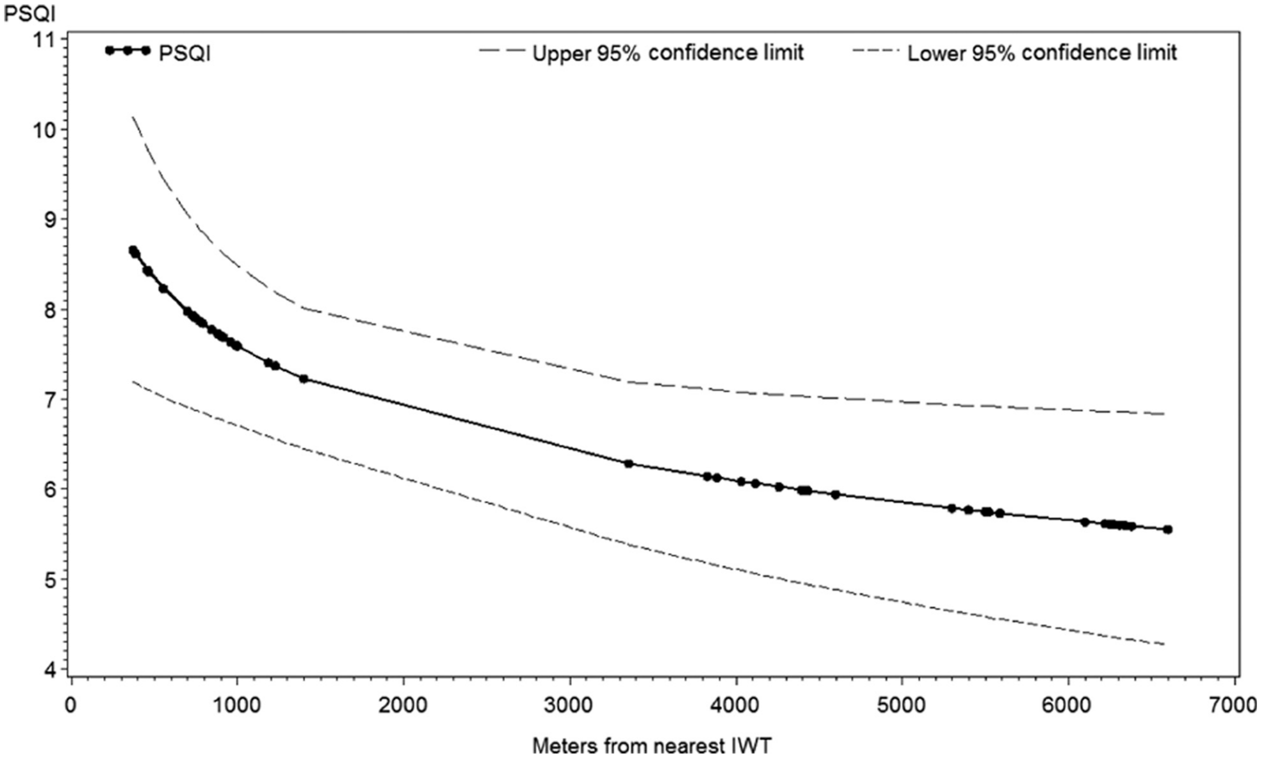

Fig. 6a Mean Pittsburgh Sleep Quality Index (PSQI) scores as a function of setback distance. The dashed lines are 95% confidence intervals.
Source: From Nissenbaum, Aramini, and Hanning.[48]

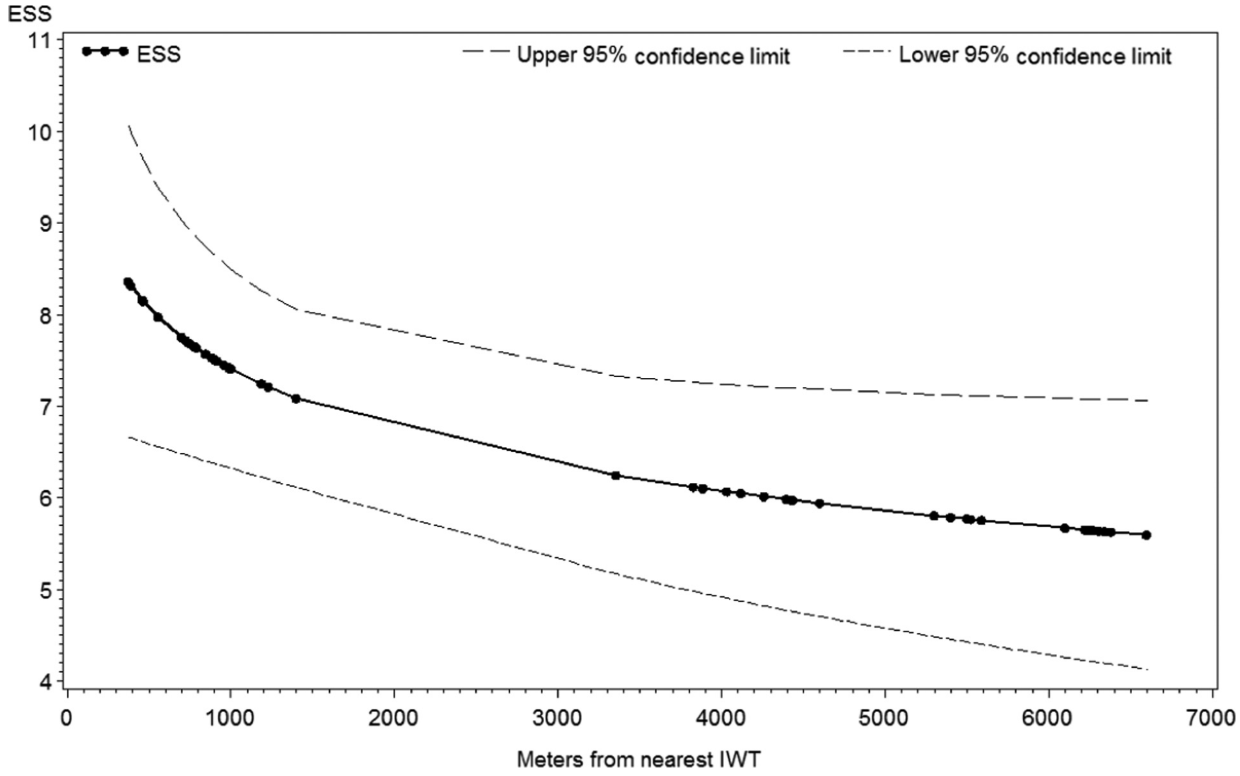

Fig. 6b Mean Epworth Sleepiness Scale (ESS) scores as a function of setback distance. The dashed lines are 95% confidence intervals. **Source:** From Nissenbaum, Aramini, and Hanning.[48]

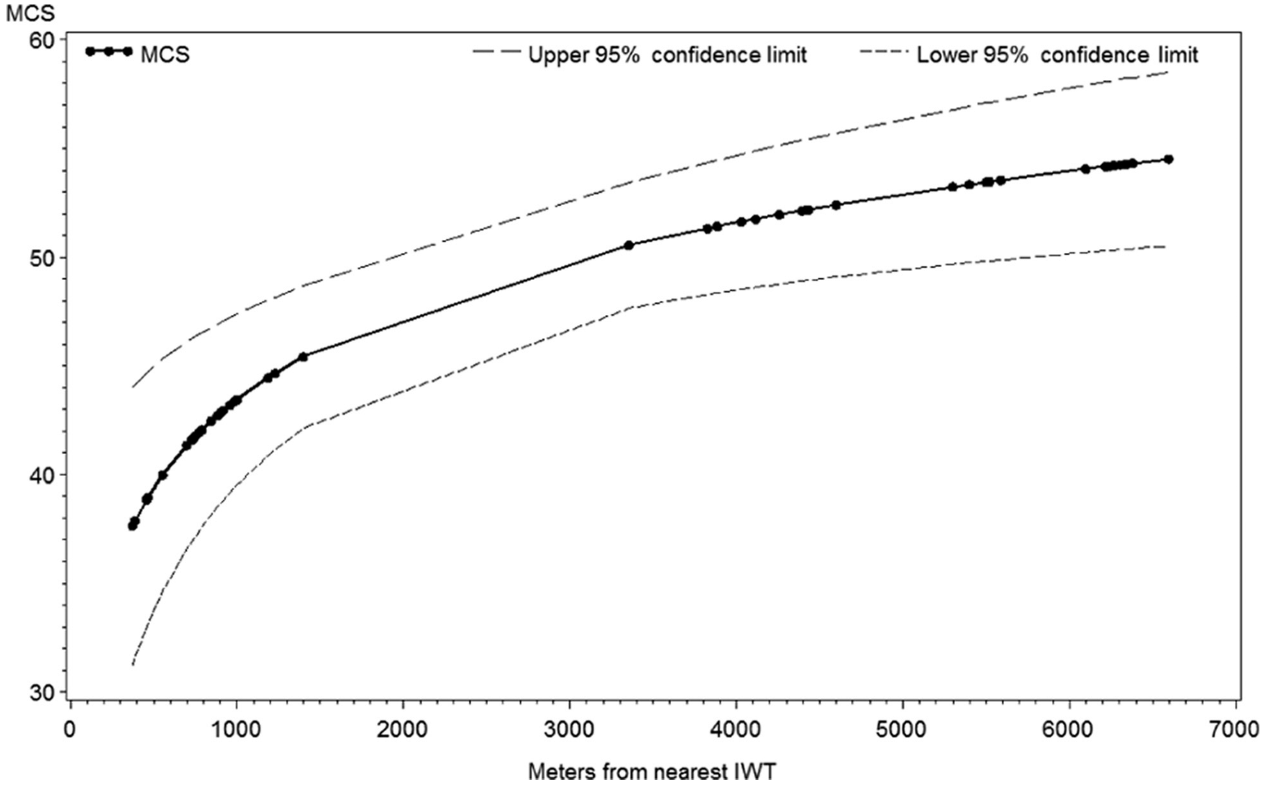

Fig. 6c Mean SF36 mental component score (MCS) as a function of setback distance. The dashed lines are 95% confidence intervals. **Source:** From Nissenbaum, Aramini, and Hanning.[48]

and thus, relying on reported awakenings underestimates the magnitude of the noise effects. The likelihood of an arousal depends upon the volume, character, and duration of the noise as well as the sleep stage and individual propensity (i.e., noise sensitivity). In an investigation into hospital noise, dose–response curves were created for different noises in different sleep stages.[50] Noises with characteristics designed to alert (e.g., telephone, alarms) were more likely to arouse. These noises tend to be impulsive in character, as does wind turbine noise. Noises that were classified as continuous broadband noises (e.g., traffic noise) were less likely to arouse. Another study[51] has shown that subjects with fewer sleep spindles (electrophysiological markers characteristic of stage II sleep) are more easily aroused by noise (Fig. 7). Sleep spindles are taken as a marker of sleep stability and may provide a physiological marker of sleep quality.

To date, there are no electrophysiological studies of wind turbine noise on sleep. However, it is reasonable to expect that, in common with road, rail, and aircraft noise, it will induce arousals, fragmenting sleep, as well as preventing the onset of and return to sleep. The sleep measures used in the study by Nissenbaum, Aramini, and Hanning[48] (i.e., ESS and PSQI) are average scores, determining sleepiness and sleep quality, respectively, over a period of weeks. Thus, occasional sleep disturbance would not alter scores as the sleep loss would have been compensated quickly over one or two nights. The study results imply strongly that sleep was being disturbed to some degree on sufficient nights to prevent compensation occurring, thus leading to persistent daytime symptoms.

Wind Turbine Syndrome

Wind turbine syndrome refers to a cluster of symptoms, which Pierpont,[24] who coined the phrase, claims are associated with exposure to wind turbine noise. Using direct clinical case studies, Pierpont describes the following symptoms to be characteristic of many individuals residing in close vicinity of wind turbines: insomnia, headaches, dizziness, unsteadiness, nausea, exhaustion, anxiety, anger, irritability, depression, memory loss, eye problems, problems with concentration and learning, and tinnitus. Pierpont hypothesizes that wind turbines may affect the vestibular system, that part of the inner ear that plays an important role in the maintenance of balance and stable visual perception. Wind turbines may compromise this system in two ways: first, by the visual disturbance of the moving blades and shadows (i.e., the flicker), and second, by direct vibration of the vestibular system. Such a model would explain why some residents in the close proximity of wind turbines (i.e., less than a kilometer) complain of vertigo, dizziness with nausea, and migraines. Wind turbine syndrome awaits further validation from the medical and scientific establishments, specifically the confirmation of a cause-and-effect relationship between wind turbine noise and vestibular function.

Wind Turbine Noise and Low-Frequency/ Infrasound Components

Recent enquiry has focused on the impacts of low-frequency (20–200 Hz) and infrasonic frequencies (typically taken as

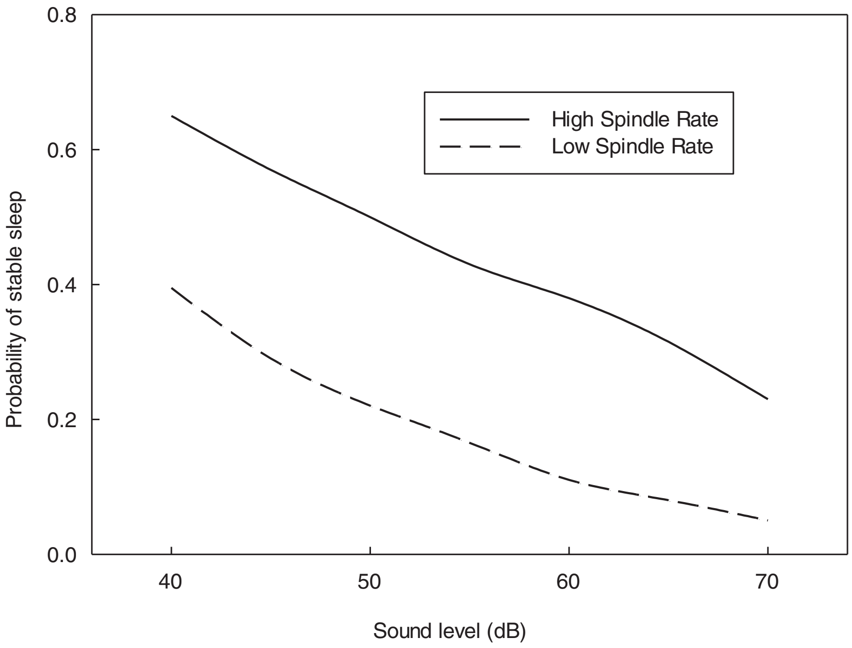

Fig. 7 Sleep stability as a function of sound level for noise-resistant (high-spindle) and noise-sensitive (low-spindle) groupings.
Source: Estimated from Dang-Vu et al.[51]

below 20 Hz) being emitted by wind turbines. Infrasound is characterized by fluctuating pressure sensations at the eardrum, is atonal and countable, and is of a level proportional to wind speed.[21] Low-frequency acoustic waves emitted by wind turbines may be amplified by ground reflection and originate from varying lift forces as the rotors travel through spaces differing in wind speed and density.[21] Compared with medium (i.e., 250 to 4000 Hz) and high frequencies (above 4000 Hz), low-frequency energy decays slowly with distance, is less attenuated by conventionally designed structures, causes certain building materials to vibrate, and can sometimes resonate within rooms and undergo amplification. The effect of air absorption must also be taken into account, in which higher frequencies are attenuated at a greater rate as a function of distance, resulting in a shifting of the spectrum toward lower frequencies. The relationship between low-frequency wind turbine noise and building type creates an interesting proposition in which the low-frequency sound may be louder inside a dwelling than out,[21,52] and the assumption that walls and windows attenuate sound by 15 dB may not be applicable to frequencies below 200 Hz.

Research has shown that low-frequency noise increases cortisol levels in those who are sensitive to noise[12] and disturbs rest and sleep at levels below noise otherwise free from lower-frequency components.[31] Low-frequency noise and infrasound are known disturbers of sleep; however, the contribution, if any, of the low-frequency noise emissions of wind turbines to the sleep disturbances they induce remains to be scientifically determined. Beyond infrasound, the phenomenon of vibroacoustic disease is worthy of note. Humans chronically exposed to infrasound may exhibit elevated cortisol levels and generalized cell damage: a condition known as vibroacoustic disease.[53] A number of human and animal models explaining how infrasound can lead to cardiovascular and respiratory disease have been proposed[54] and applied to wind turbine noise.[55] The phenomenon of vibroacoustic disease is supported by correlational evidence coupled with a thoroughly detailed mechanism. However, further research is required to establish the veracity of this approach to human health within and beyond the wind turbine context.

MITIGATION

There are multiple ways in which to reduce the impacts of audible and inaudible wind turbine noise. The first, and often the most effective, method is to control audible noise at the sound source. Thus, mechanical solutions invite technologies designed to attenuate wind turbine noise or to shift its spectral character in order to eliminate salient tonal characteristics. To safeguard health is more difficult, however, because wind turbine noise is largely aerodynamic in origin,[7] and it is not possible to obtain solutions that completely attenuate the noise at its source. Having minimized the noise through the implementation of technology, other approaches are often required, normally involving the application of noise standards to limit exposure levels or the determination of "safe" setback distances to mitigate noise impact. Still other approaches involve the positioning of wind turbines around preexisting noise generators,[15] in remote areas away from human habitations, or using social processes to determine wind turbine location.[27,56]

Regulating Permissible Noise Level

Permissible or safe exposure levels are often set in national noise standards, which may or may not be specific to wind turbine noise. These standards may serve one of two purposes, or sometimes both, with noise compliance guidelines naturally emerging from the two. The first purpose relates to methodologies for the physical quantification of the noise. This may involve standardized procedures for measuring noise from preexisting windfarms or detailing accepted mathematical models affording noise predictions of a planned windfarm. The second purpose is to determine what exposure levels can be considered safe and to clearly state criteria to this effect. However, there are a number of flaws inherent in wind turbine noise standards, including the metrics used to represent the noise, oversimplified modeling approaches that yield unrealistically low predictions of noise levels representing "best case" conditions,[5] or stimulus-oriented approaches that fail to account for human factors.[3,57]

There exists, in respect to levels-based noise standards, disagreement as to the relevance of physical measures such as dBA to human response,[58] not only for windfarm noise (Pedersen, 2008b) but also for traffic and aviation noise. Of the few parametric studies that have been published,[7,8] only marginal dose–response relationships between wind turbine noise intensity and health measures have emerged. For example, Pedersen[22] noted that stress was not related to wind turbine noise level but rather noise annoyance. Persson Waye and Öhtrsöm[12] reported that annoyance ratings varied for five distinct recordings of wind turbine noise, even though all five had equivalent noise levels. Others note that both laboratory and field studies have consistently found that the equivalent dBA measure fails to account for the relationship between wind turbine noise and annoyance.[14]

To some degree, then, it must be accepted that there is an uncoupling between wind turbine noise level and human response. A hitherto rarely measured characteristic of wind turbine noise is amplitude modulation, whereby noise levels fluctuate periodically as a function of blade passing frequency. Lee et al.[34] recommend that standardized metrics based on the modulation depth spectrum be developed and used in conjunction with sound levels. Other approaches to measuring amplitude modulation have existed for some time[4,59] but have yet to be seriously applied to the wind turbine noise context. However, the inability to account for amplitude modulation arises primarily due to the time-averaged dBA levels applied by noise standards, and arguably, smaller sampling epochs of around 100 msec should be adopted as best practice in order to record the amplitude modulation inherent in turbine noise.[60,61] The New Zealand Standard[62] applies a penalty for amplitude modulation, but does not describe an objective assessment. Furthermore, using aggregated metrics that average noise level over long periods underestimates the effect of peak levels and crest factors, important when considering sleep disturbance.

For the most part, the acceptable noise limits recommended by noise standards are derived from WHO guidelines.[31,63,64] However, as Fig. 8 demonstrates, using recommended noise levels from guidelines based on transport data risks exposing the population to unacceptable levels of noise. It follows that the Ldn (the "day–night" level in the United States) or Lden (the "day–evening–night" level in Europe) measures, derived from the measured L_{Aeq} sound level can be used in a wind farm context, but with caution.[65] Inspection of Fig. 8 suggests that, relative to transport guidelines, at least a 10 dBA penalty should be placed on wind turbine noise. The differences in annoyance ratings between wind turbine noise and transport noise maybe accounted for by amplitude modulation, the typical location of windfarms (e.g., rural areas), or the over-representation of noise-sensitive individuals. A recent meta-analysis of three epidemiological studies revealed a consistent trend in wind turbine noise exposure and both annoyance and sleep disruption.[22] On the basis of her analysis, Pederson recommends that outdoor levels should not exceed 40 dBA, though this level could be more-or-less depending on situational factors, that is, ambient noise levels or the building's construction materials. When noise is continuous, the WHO[31] stipulates an indoor limit of 30 dBA, though for noises containing lower frequencies (e.g., wind turbine noise), a lower limit still is recommended. Thus, careful examination of the lower end of the frequency spectrum is important when judging appropriate exposure to wind turbine noise, and the use of dBC or spectral analysis in one-third octave bands or narrow bands is necessary.

In the comparison of global wind turbine noise level standards, there exist two chief methodologies, namely, sound levels not to be exceeded (usually in dBA) or a not-to-be-exceeded limit derived from the sum of the preconstruction ambient limit and a constant (e.g., L_{A90}+10 dBA). Critique of both these approaches can be found in Thorne.[3] The fact that noise limits differ between, and even within, a country is testament to the impoverished research database guiding their development or the political sensitivities around wind turbine placement. Examples of noise limits are presented in Table 3, and the variability in guidelines is evident. Based on the authors' collective experience, an interim guideline, providing a conservative noise limit capable of protecting the health of the public and suscep-

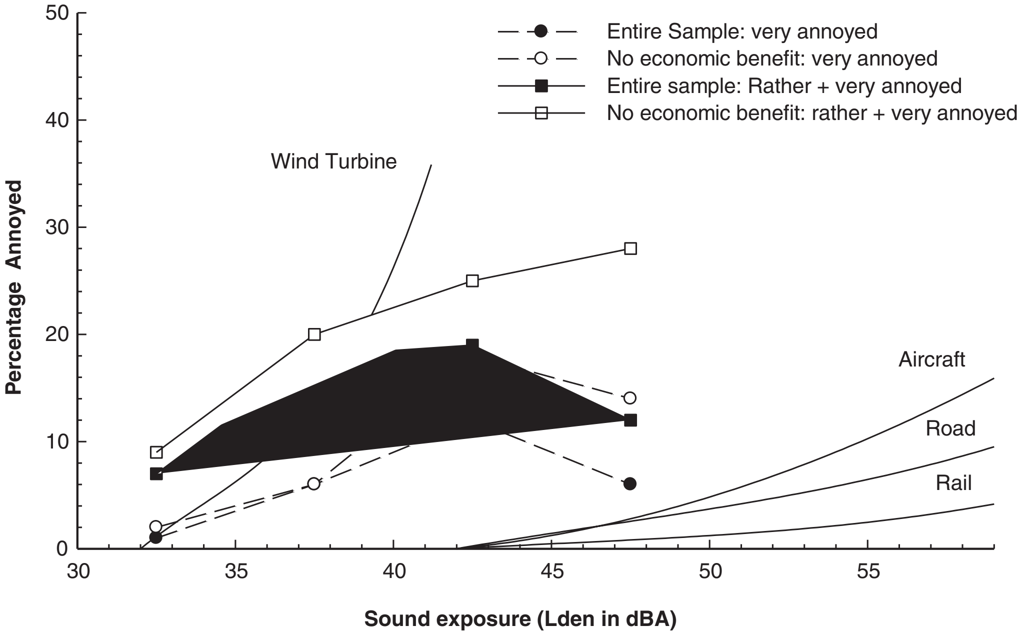

Fig. 8 Annoyance plotted as a function of noise level for four theoretical models (rail, road, and air parameters: Miedema and Oudshoorn;[66] wind turbine parameters: Pedersen et al.;[7] and four sets of data obtained from Tables 7.24–7.26 of van den Berg et al.[8]). For the data, closed symbols are for the entire sample, while open symbols are for those who identified that they had no economic interest. Circles represent the percentage of "very annoyed" responses, while squares represent the sum of "very annoyed" and "rather annoyed" responses.

Table 3 A comparison of wind turbine noise guidelines taken from nine countries.

Country	State	Limit (dBA)	Background plus constant
Australia	Victoria	L_{A90} 35 or 40	L_{A90} + 5 dBA
	South Australia	L_{Aeq} 35 or 40	L_{A90} + 5 dBA
Australia	Queensland	L_{Aeq} 30 indoors	Health and well-being criteria
Canada	Ontario	L_{Aeq} 40 to 51	
Denmark		40	
France			Day: L_{A90} + 5 dBA Night: L_{A90} + 3 dBA
Netherlands		40	
New Zealand		L_{A90} 35, 40	L_{A90} + 5 dBA
United Kingdom		Day: 40 Night: 43	L_{A90} + 5 dBA
United States	Illinois	Day: 50 Night: 46	
	Michigan	55	
	Oregon	35	

tible individuals, would be a sound level of L_{Aeq} 35 dBA outside the residence and below the individual's threshold of hearing inside a residence. More specific guidelines are presented in Appendix A of this document.

Regulating Setback Distances

A setback distance is defined as the minimum distance between a dwelling and the closest wind turbine required to protect the health of the inhabitants. One difficulty is whether such setback distances can be standardized, as they will differ depending on a number of factors, including turbine type, terrain, and climate. Lee et al.[34] report that the perception of amplitude-modulated noise decreases with distances beyond a kilometer, though others claim that amplitude-modulated turbine noise can be heard up to 4 km away from the source.[67] Setback distances maybe based on noise level, which, as discussed in the preceding section, maybe an invalid approach. Instead, a better approach may be to link setbacks to turbine type. Møller and Pedersen,[21] investigating the detection and annoyance of lower-frequency sound emitted from wind turbines, suggest that, for flat terrain, the minimum setback distance for modern turbines (2 to 3.6 MW) should be between 600 and 1200 metres. Other approaches rely on the establishment of dose–response curves relating a health outcome variable (e.g., annoyance or disturbed sleep) and distance (e.g., Fig. 6). Medical professionals have proposed setback distances of 2.4 km[23,24] or 1.5 km.[45] Other research recommends a minimum of 2 km if wind turbines are sited in rough terrain.[3,20]

CONCLUSION

Windfarms have significant potential for sleep disruption and annoyance due to the intermittent nature and amplitude modulation of their sound emissions, even though exposure may be of low amplitude. The interactions between ambient levels, amplitude modulation, and the tonal character of windfarm noise overlaid within a soundscape are complex and difficult to measure and assess in terms of health and individual amenity. Additionally, currently employed sound level measurement and prediction approaches for complex noise sources of this nature are only partially relevant to environmental risk assessment. Aside from acoustic parameters, other factors such as noise sensitivity or amenity expectations may also predict the human response to wind turbine noise. Unfortunately then, for policymakers, there appears to be no proportional relationship between wind turbine noise levels and health, as these outcome factors will be influenced by characteristics associated with both the noise and the listener.[39]

As a relatively new source of intrusive noise, there is little research to draw upon when judging if a proposed windfarm constitutes a health threat to the exposed public. A liberal approach to assessing health impact will involve the application of previous knowledge obtained from other noise sources (e.g., road, aviation). A conservative approach, consistent with the precautionary principle, will consider wind turbine noise more potent than these other harmful noise sources. Thus, at this time, a constellation of acoustic and social metrics should be taken at preexisting wind farms in order to assess potential threat. Peak and crest noise levels, level metrics assessing low-frequency contributions (e.g., dBC), and amplitude modulation indices constitute the acoustic measures of importance. It should also be remembered that predicted levels derived from computer models represent estimates and not precise values, are constrained by numerous assumptions, contain substantial uncertainty, and as such should not constitute the sole criteria for wind turbine positioning. What form the social measures will take is yet to be elucidated, but research suggests that noise sensitivity[67] and procedural fairness[27] are the best approaches to minimize the health impacts and facilitate social acceptance of windfarms.

ACKNOWLEDGMENTS

The authors thank Rick James of E-Coustic Solutions for sharing his acoustical expertise on the matter of wind turbine noise guidelines.

APPENDIX A

‘Proposed Wind Turbine Siting Sound Limits’, a revision by Thorne, R, of the Kamperman James criteria (2008) to include updates to ISO 1996-2 and UK Court of Appeal (Hulme re: Den Brook).

1. Audible Sound Limit
   - **a.** No wind turbine or group of turbines shall be located so as to cause an exceedance of the pre-construction/operation background sound levels by more than 5 dBA. The background sound levels shall be the L_{A90} sound descriptor measured during a pre-construction noise study during the quietest time of evening or night. All data recording shall be a series of contiguous ten (10) minute measurements. L_{A90} results are valid when L_{A10} results are no more than 15 dBA above L_{A90} for the same time period. Noise sensitive sites are to be selected based on wind development’s predicted worst-case sound emissions in L_{Aeq} and L_{Ceq} which are to be provided by the developer.
   - **b.** Test sites are to be located along the property line(s) of the receiving non-participating property(s).
   - **c.** A 5 dB penalty is applied for tones as defined in IEC 61400-11 at the turbine and ISO1996-2 at any affected residence.
   - **d.** A 5 dB penalty is applied for amplitude modulation as defined following. When noise from the wind farm has perceptible or audible characteristics that are perceived by the complainant as being cause for complaint, or greater than expected, the measured sound level of the source shall have a 5 dB penalty added. Audible characteristics include tonal character measured as amplitude or frequency modulation (or both); and tonality (where the tonal character/tonality of noise is described as noise with perceptible and definite pitch or tone). Amplitude modulation is the modulation of the level of broadband noise emitted by a turbine at blade passing frequency. Amplitude modulation will be deemed greater than expected if the following characteristics apply:
     - **i)** A change in the measured L_{Aeq}, 125 ms turbine noise level of more than 3 dB (represented as a rise and fall in sound energy levels each of more than 3 dB) occurring within a 2 second period.
     - **ii)** The change identified in (i) above shall not occur less than 5 times in any one minute period provided the L_{Aeq}, 1 minute turbine sound energy for that minute is not below 28 dB.
     - **iii)** The changes identified in (i) and (ii) above shall not occur for fewer than 6 minutes in any hour.

   Noise emissions are measured outside a complainant’s dwelling and shall be measured not further than 35 metres from the relevant building, and not closer than within 3.5 metres of any reflective building or surface, or within 1.2 metres of the ground.

2. Low Frequency Sound Limit
   - **a.** The L_{Ceq} and L_{C90} sound levels from the wind turbine at the receiving property shall not exceed the lower of either:
     - **i)** L_{Ceq} -L_{A90} greater than 20 dB outside any occupied structure, or
     - **ii)** A maximum not-to-exceed sound level of 50 dBC measured as the background sound level (L_{C90}) from the wind turbines without other ambient sounds for properties located at one mile or more from State Highways or other major roads or measured as the background sound level (L_{C90}) for properties closer than one mile.
     - **iii)** These limits shall be assessed using the same night-time and wind/weather conditions required in 1(a). Turbine operating sound emissions (L_{Aeq} and L_{Ceq}) shall represent worst case sound emissions for stable night-time conditions with low winds at ground level and winds sufficient for full operating capacity at the hub.

3. General Clause
   - **a.** Sound levels from the activity of any wind turbine or combination of turbines shall not exceed L_{Aeq} 35 dB within 100 feet of any noise sensitive premises.
   - **b.** The monitoring shall include all the sound levels as required by these noise conditions and shall include monitoring for the characteristics described in Annex A of IEC 61400-11including infrasound, low-frequency noise, impulsivity, low-frequency modulation of broad-band or tonal noise, and other audible characteristics. Wind speed and wind direction shall be measured at the same location as the noise monitoring location.

4. Requirements
   - **a.** All instruments must meet ANSI or IEC Class 1 integrating sound level meter performance specifications.
   - **b.** Procedures must meet ANSI S12.9, IEC61400-11 and ISO1996-2
   - **c.** Procedures should meet ANSI, IEC and ISO standards applicable to the measurement of sound or its characteristics.
   - **d.** Measurements must be made when ground level winds are 2m/s (4.5 mph) or less. Wind shear in the evening and night often results in low ground level wind speed and nominal operating wind speeds at wind turbine hub heights.

e. IEC 61400-11 procedures are not suitable for enforcement of these requirements except for the presence of tones near the turbine.

5. Definitions

ANSI S12.9 Quantities and Procedures for Description and Measurement of Environmental Sound, Parts 1 to 6.

IEC 61400-11 *Wind turbine generator systems—Part 11: Acoustic noise measurement techniques.*

ISO 1996-2 *Acoustics—Description, measurement and assessment of environmental noise—Part 2: Determination of environmental noise levels*.

L_{A90}, L_{A10} Statistical measures calculated under ANSI S12.9.

L_{Aeq}, L_{Ceq} Time average levels calculated under ANSI S12.9 or ISO 1996-2.

Noise sensitive premises includes a residence, hotel, hostel or residential accommodation premises of any type.

6. References

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Proceedings of Meetings on Acoustics

Volume 30 http://acousticalsociety.org/

Acoustics `17 Boston

173rd Meeting of Acoustical Society of America and 8th Forum Acusticum
Boston, Massachusetts
25-29 June 2017

Noise: Paper 4aNSb3

A possible criterion for wind farms

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Opposition to wind farm noise is not abating and shows no sign of doing so in the future. In a January 2017 paper in Sound and Vibration, Hessler, Leventhal, Walker and Schomer come together to report that independently they have come to about the same conclusion for a proper threshold of wind turbine noise. The same A-Weighted criterion has shown to come up in a variety of independent ways. This paper is not for pie in the sky desires for no sound. Rather, it attempts to recommend a criterion to use for determining the limits of wind turbine noise. This criterion is based off of the data of four independent sources: (1) CTL, (2) ANSI S12.9 Part 4, (3) Michaud et al. (2016), and (4) a State of Minnesota Department of Commerce survey of criteria set in various foreign countries and provinces. This paper recommends the use of A-weighting and a 24-hour Leq as the metric. 36-38 dB is recommended for the criterion.

Published by the Acoustical Society of America

https://doi.org/10.1121/2.0000590
Proceedings of Meetings on Acoustics, Vol. 30, 040007 (2017)

1. INTRODUCTION

A. BACKGROUND

Like most other industries or sources of transportation, noise and noise criteria are a matter of consternation to all sides involved in the siting and development of wind farms. Industry wants the permitted acoustical levels as high as possible, the community wants them as low as possible, and the municipality or county wants to maximize the dollars in their budget. For the past 10 or 15 years there has been an evolution towards developing a metric and criterion for wind turbine noise. Many turbines were built with what turns out to be rather high levels. They were designed with the community level being set at 50 or even 55 dB (A). Gradually, these levels have decreased, but friction between the community groups, the developers of the wind farms, and local government continues to this day.

B. PURPOSE

The purpose of this paper is to explain and evaluate the metric by which the community response to wind turbine noise is gauged and the limits appropriate to that response function. Chapter II deals with selection of the metric, and Chapter III presents the data and methods used to establish criteria and a criterion, based on the metric selected.

C. APPROACH

The approach to the selection of a metric is pragmatic. When looking at the present situation, A-weighting is the only appropriate metric for most noise sources. Based on all that we know, it could well be that C-weighting is preferred, or even Z-weighting or lower would be an improvement. But pragmatically, what is in use today and has corresponding response functions is A-weighting. These issues are dealt with in Chapter II.

In the second and more major part of the paper, various *independent* references and their procedures are used to find data on which to base the selection of a recommended criterion. These data come from four very independent sources. The use of four totally independent sources of data, independent from each other and independent from the issues at hand cannot be stressed enough. For example, the community tolerance level (CTL) was developed based on road traffic and airport noise, totally independent of wind turbine noise (WTN), totally independent of American National Standards Institute (ANSI) S12.9 Part 4, totally independent of the Health Canada study, and totally independent of the Minnesota Department of Commerce study. Similar statements can be made of each of the four sources, and these four sources are equally independent from the parties concerned (industry, community, and local government). They are totally independent of the results from the ANSI S12.9 Part 4 calculation, because these results were developed without having wind turbines mentioned or included in any way, as this was just a general procedure for environmental noise. Any assessment here is certainly independent from the Minnesota Department of Commerce existing criteria levels. The average and extremes of those data are what they are; nothing we do here can influence that. CTL is derived for other sources and other places, and not constructed for WTN, so its application is totally independent from wind turbine noise sources. The Health Canada data are not totally independent of the issues at hand, but the authors argue that the Health Canada data are equally independent for all three parties. In the same test with the same subjects, the Health Canada study finds that there are no health effects that can be found at the resolution that one gets with about 1200 subjects, but that there are substantial annoyance effects with these same subjects in the same study. One finding for industry, one finding for the community. That is, with the same sampling, the same noise measurements, the same noise predictions, the same surveyors, the same survey instrument, the same subjects, one gets half of the results that in some sense support industry, and half of the results that in some sense support the community. At least to this authors' mind, Health

Canada represents an independent government entity not aligned with any of the three parties. The four sources are as follows:

1. data inherent to community tolerance level (CTL);
2. ANSI S12.9 Part 4
3. data from Health Canada, used to establish the equivalency between wind turbine noise and other noise;
4. the Minnesota Department of Commerce

Note: None of the data was developed by these authors and each of the sources is independent from any of the three primary groups involved: community, developer/operator, and local government. Thus, our approach is to present and explain these sets of data or procedures, and to show how they relate to the general method and the criterion that is ultimately selected.

1. CTL provides a one-number assessment of a set of cluster data from an attitudinal survey. Depending on what is held constant, almost any situation can be compared in decibel units of day-night level (DNL). Keeping with current practice, road traffic noise is used as the baseline. The difference in CTL between a data set under study and road traffic noise is the decibel difference between the two CTL values, respectively.
2. ANSI S12.9 Part 4 is directly used to form a small range of levels for potential development of a criterion.
3. Direct use of the Michaud *et al.* data and other similar international data to set a criterion.
4. Data from a State of Minnesota Department of Commerce survey of criteria set in various foreign countries and provinces.

2. SELECTION OF A METRIC

A. DISCUSSION OF WEIGHTING

As is well known, most sources are assessed using A-weighting with perhaps an adjustment for sound character (e.g. tonal or impulsive). A basic version of this assessment metric has been used since at least 1971 when the first version of ISO 1996 (International Organization for Standardization) was approved. The only source for which A-weighting is not used is high-energy impulsive noise, e.g. sound from demolition, open pit mining and quarrying, sonic booms, and noise from military training. For these sources, C-weighted data are collected, and these data are transformed to equivalent A-weighted levels in terms of equal annoyance (ANSI S12-9, ISO 1996-1).

There is no function that relates C-weighted wind turbine noise to an equivalent A-weighted level, nor is there a function that relates Z-weighting to an equivalent A-weighted level. The C-weighting procedure for high-energy impulsive noise took about 25 years to validate and get into use. Correlation between A-weighting and C-weighting in response to turbine noise has been shown, but this does not show that either of the weightings is correct. There is no conversion tool upon which to develop equivalent A-weighted levels. A response function is required. But it can be observed that a high degree of correlation between A- and C-weighting exists; so high that there is virtually no difference between using C-weighting or A-weighting. When one has a class of sources that all have the same spectrum, then the difference between different linear filters that all measure at least some part of the sound will all be highly correlated with one another. The difference between A-weighting and other weightings is that response functions have been created and scrutinized for A-weighting.

A constant, 24-hour A-weighted equivalent level (Leq) computed over the day and night periods, is the recommended metric, and in nearly all cases, the metric of interest is the nighttime Leq resulting from wind farm operations. So, as with aircraft and other noise categories that are dominated by one kind of source, comparisons can be made from one situation to another because the spectral content has not changed from one situation to another. For example, if one is measuring traffic noise, then the Leq for the hour beginning at 1500 measured on Tuesday should be similar to the hour measured at 1500 on Wednesday.

If the appropriate computational procedures are chosen, then one can install a barrier, have a reasonable chance at predicting a reduction, and subsequently produce a meaningful reduction for the community. That is not the situation with wind farm noise. It has been shown that the correlation from one type of wind turbine to another, and from one size to another, results in a set of numbers that properly order different situations because there is no change to the spectrum from one wind turbine to another. But this is not the case if one performs mitigation and predicts the benefit based on A-weighting. A barrier can be built alongside a highway and the reduction can be predicted. The corresponding decrease in community annoyance can also be predicted, at least to a reasonable degree. We cannot make the same statement about wind farm noise.

The reader should be cautioned not to believe that A-weighting is the correct weighting function for wind farm noise assessment. This simply has not been shown. Currently, however, the A-weighted levels assigned to different community responses seem to fit current wind farms in terms of response and level, at least in terms of annoyance based on attitudinal survey data. A-weighting is not chosen because it has been shown scientifically to be better than other metrics. Rather, it is chosen because at the current state of development, to date, no one has shown any metric to be superior. Even if it were available today, it would still take quite a while to gain acceptance for such a metric.

B. METRIC

The choice of a metric is limited. In principle, all of the readily available noise metrics are those built into sound level meters and other similar devices. The non-time integrating metrics are very limited in the data provided. Lmax and Lmin are two non-integrated choices, but it is clear that Lmax may be something that occurs for a short time every once in a while (e.g., once an hour or once a day). In the class of time-integrated metrics, there are three prominent choices: Leq, Ldn, and Lden. These three are not significantly independent; rather, there are very clear and consistent differences among them. Leq 24-hour is predicated on the assumption that wind farm noise emissions from a given turbine throughout the 24-hour day are more or less constant (read ±1 dB). The question is: how far above Leq must the DNL be such that the calculation of Leq during daytime added to (Leq+10) dB at night equals to DNL? The difference between the numerical value for Leq and DNL when the Leq is held constant is about 6-7 dB. A similar number exists for DENL. DNL or DENL provide no additional information as compared to the simpler, constant 24-hour Leq. Were Leq not a constant, and Ld and Ln are not constant, then a more complicated difference between DNL and 24-hour Leq would be required.

3. METHODS AND PROCEDURES BY WHICH A CRITERION FOR WIND TURBINE NOISE CAN BE SELECTED

A. DIFFERENCES IN COMMUNITY TOLERANCE LEVEL (CTL) BETWEEN ROAD TRAFFIC AND WIND TURBINE NOISE

At this point, it is proposed that a relationship between percent highly annoyed and various nighttime Leq levels be established. However, the recent papers by Fidell et al. and Schomer et al. relate percent highly annoyed to DNL. These two papers also introduce the concept of community tolerance level (CTL). This paper will establish the relationship between nighttime Leq, CTL, and DNL for wind turbine noise. Once that is done, we will compare various DNL and CTL levels with wind farm levels. As a part of this comparison, we will include the transformation of CTL or DNL data to nighttime Leq in order to have valid comparisons. First, DNL will be discussed, followed by CTL.

Up until the introduction of CTL, all community attitudinal survey data were analyzed by using linear regression analysis. There was no underlying functional relation. With CTL, it is hypothesized that the community response to environmental noise is similar to the basic human loudness function where loudness is proportional to the independent variable raised to the 0.3 power. Secondly, it is hypothesized that the functional form of a relationship is a transition function, and for the sake of simplicity, the simplest form of a transition function is used: e^{-v}. It becomes:

$$\%HA = 100 * e^{-1/(10^{\left(\frac{Ldn-Lct+5.306}{10}\right)^{0.3}})} \qquad (1)$$

where 5.306 is an arbitrary constant K. The property of K is such that when Ldn=Lct, then Lct corresponds to the 50th percentile for %HA. That is, for purposes of convenience, the value of CTL for a given community is standardized at the midpoint of the exponential function. A CTL value thus corresponds to the DNL value at which half of the people in a community describe themselves as highly annoyed by transportation noise exposure. As Fidell *et al*. (2011) show, the constant 5.306 follows from the definition of CTL as the midpoint of the exponential function. That is, when DNL = CTL, the %HA = 50%. (Definition of CTL at a point other than 50% on the exponential function would merely result in a change to the constant 5.306, with no loss of generality.)

Fidell *et al.* (2011) gives the percent highly annoyed as a function of DNL for all noise caused by airport operations. Schomer *et al.* (2012) does the same for highway and railroad noise. The convention is that all noises are compared to road traffic noise. The difference in the value of K between any source and road traffic yields the numerical difference in dB between the two situations. For example, the CTL for all road traffic is 78 dB and the CTL for all aircraft is 73 dB. So, aircraft is 5 dB less tolerable than road traffic noise. CTL can quantify the difference between any two situations one wants to consider. For example, one could look at the difference between nighttime and daytime, the difference between hilly country and flat country, the difference between urban, suburban, and rural, or the difference between communities on the ocean and those landlocked.

Michaud *et al.* (2016) calculates the CTL for wind turbine noise to be 62 DNL. That is, 16 dB must be added to the DNL of road traffic noise to make it equivalent to that of wind turbine noise. Michaud et al. also calculate the CTL for each of his two study areas, Prince Edward Island and Ontario, independently. In addition, they calculate the CTL for other surveys that provide the necessary data to calculate the CTL (Pedersen et al. 2004, 2007, 2009; Yano et al. 2013). Michaud shows that the CTL for Ontario is very similar to the CTL for Pederson et al., 2004 and Yano et al. 2013. The CTL for PEI is shown to be very similar to the CTL for Pederson et al 2007 and 2009. The CTL for Ontario is about 7.5 dB lower than the CTL for PEI. They also compute the average CTL for windfarms and that is what is used herein.

B.USE THE DIRECT HEALTH CANADA AND THER COMPARABLE INTERNATIONAL SURVEY DATA OF %HA AT VARIOUS TURBINE NOISE LEVELS

This method is the simplest, it says that the %HA at a certain dB(A) is exactly what is measured. There are three data points provided by the Health Canada analysis: the ranges are from [30-35) dB, [35-40) dB, and [40-46) dB. The corresponding %HA are 1%, 10%, and 14%.

In this paper, several primary sources of data are used to develop the functional relationship and select the criteria. Once a DNL is chosen as the metric, the second step is to establish percent highly-annoyed as a function of DNL. This %HA can then be compared to the results from Michaud *et al.* to form a criterion.

C. USE THE S12.9 TO DIRECTLY DEVELOP A CRITERION

ANSI S12.9 Part 4 uses DNL as its primary metric. ANSI S12.9 Part 6 establishes 55 DNL as the criterion for start of impact from noise. Part 4 also establishes the adjustment of 10 dB for quiet rural areas, i.e. the criterion drops to 45 DNL. In terms of a 24-hour A-Leq, this criterion drops to 39 dB. So, we find 39 dB to be a criterion, independent of the noise source. This derivation never mentions wind turbine noise.

D. USE THE MINNESOTA DEPARTMENT OF COMMERCE FINDINGS

Minnesota, like 29 other states (reference 2 from Haugen 2011), has a state renewable energy objective that calls for “25% of the state’s electrical energy to come from renewable sources including wind energy by 2025 (reference 3 from Haugen 2011).” “While many people support wind energy, some have become concerned about possible impacts to their quality of life due to wind turbines, including noise, shadow flicker, and visual impacts…” Because of these concerns surrounding wind power, the state set out to survey a variety of players in the wind energy industry, from many foreign regions and countries. “For this report, a variety of professionals working on renewable energy issues within national and regional governments, wind energy associations, wind energy development companies, and other areas were contacted by email.”

The Minnesota findings are shown in Figure 1. This figure shows national and regional wind farm limits in two different kinds of areas: (1) residential and other noise sensitive areas, and (2) all other areas. These are represented in the figure as a solid blue bar for the sensitive areas, and a solid green bar going above the blue for the other areas. Only 3 of the 19 jurisdictions are above 40 dB: Spain, Portugal, and the Netherlands, and the average is 36 dB.

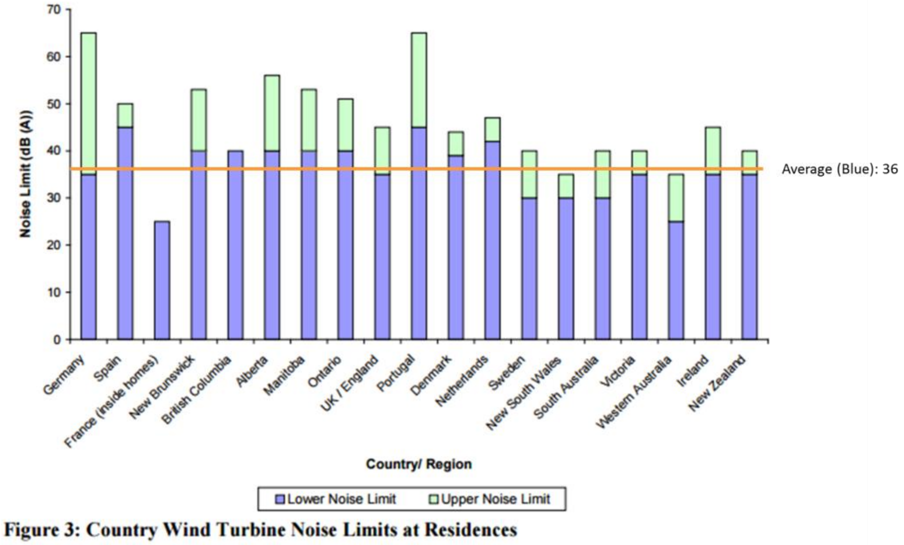

Figure 1: International wind turbine noise limits obtained by the Minnesota Department of Commerce

4. EVALUATION OF CURVES EQUATING DNL TO %HA

In this report, data from six different sources are examined in an attempt to develop a %HA criterion for wind turbine noise (and most other noises): Schultz, the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA), the Federal Interagency Committee on Noise (FICON), CTL (Fidell *et. al.*, Schomer *et. al.*), Miedema and Oudshoorn (2003), and Miedema and Vos (1997). Schultz, CHABA, and FICON are all based on the Schultz's 1978 synthesis of social surveys on noise annoyance, with the CHABA curve being virtually identical, and FICON being mysteriously low in the relevant DNL interval (60-75 DNL). Miedema and Oudshoorn is an improved version of Miedema and Vos, and along with CTL is used in the current version of ISO 1996-1. Schultz, CHABA, and FICON use data from a combination of aircraft and road traffic noise sources to arrive at their %HA values, whereas CTL, Miedema and Vos, and Miedema and Oudshoorn all make a distinction between aircraft and road traffic. The curve given by Miedema and Vos is shown in the figure for reference as a dashed blue line, but is not included in the analysis that follows because they are two variant data fits to the same data base by the same organization, and using both of them could bias the calculations that follow.

These five sources and their %HA from 50 to 70 DNL in 5 dB increments are shown in Table 1. In this table, Miedema and Oudshoorn and CTL both have separate equations for road traffic and air traffic. CHABA and FICON each use their own single equation for all modes of transportation; planes, trains, and automobiles. Research has conclusively shown that aircraft sound is more annoying than other sound for the same numerical value, which implies that the DNL values Schultz, CHABA, and FICON attribute to a corresponding percentage of high annoyance must be biased high for use with road traffic. And conversely, the %HA for aircraft noise must be biased low. Part A of Figure 2 shows the five functions described for road traffic noise, and Part B shows the five functions described for aircraft noise. From the figures, it would seem that the biased low is a much stronger factor than the biased high. In fact, from the data, one would be tempted to say there is no bias high, but from the logic, this seems to be impossible. As shown in Figure 2A, the Schultz, CHABA, and FICON curves fit somewhat closely to the road traffic curves, but understates the %HA value. For aircraft noise (Figure 2B), %HA values are understated by a very large amount, nominally 15%.

ROAD:					
Group	**M&O**	**CTL**	**CHABA**	**FICON**	**SCHULTZ**
50	3.8	0.7	2.3	1.7	1.3
55	6.6	3.1	4.6	3.3	3.9
60	10.6	8.6	8.7	6.5	8.5
65	16.5	17.6	15.2	12.3	15.2
70	25.1	29.2	24.5	22.1	24.6
AIR:					
Group	**M&O**	**CTL**	**CHABA**	**FICON**	**SCHULTZ**
50	5.3	3.1	2.3	1.7	1.3
55	11	8.6	4.6	3.3	3.9
60	18.6	17.6	8.7	6.5	8.5
65	27.8	29.2	15.2	12.3	15.2
70	38.5	41.9	24.5	22.1	24.6

Table 1: %HA values at different DNL levels for 5 sources

There is no doubt that both Schultz and CHABA represent excellent researchers and excellent organizations. Their results differ from more recent results by Miedema and Oudshoorn, Fidell, and

Schomer. The only conclusion one could come to is that the two databases being analyzed are not the same, and that is known to be the case. The database used by Schultz contained 11 clustering surveys, of which six were aircraft, four were road traffic, and one was railroad. In contrast, the three more recent curves are based on a much larger database. Fidell used 43 aircraft surveys for his work, and Schomer used 39 road traffic surveys and 11 railroad surveys, totaling 93 surveys used to create the CTL method. Miedema and Oudshoorn is based upon a similar quantity of data. A large quantity of the data is used both for CTL and Miedema and Oudshoorn. For a variety of reasons, the authors of this paper will use the methods based on the larger database, Miedema and Oudshoorn, CTL, and CHABA.

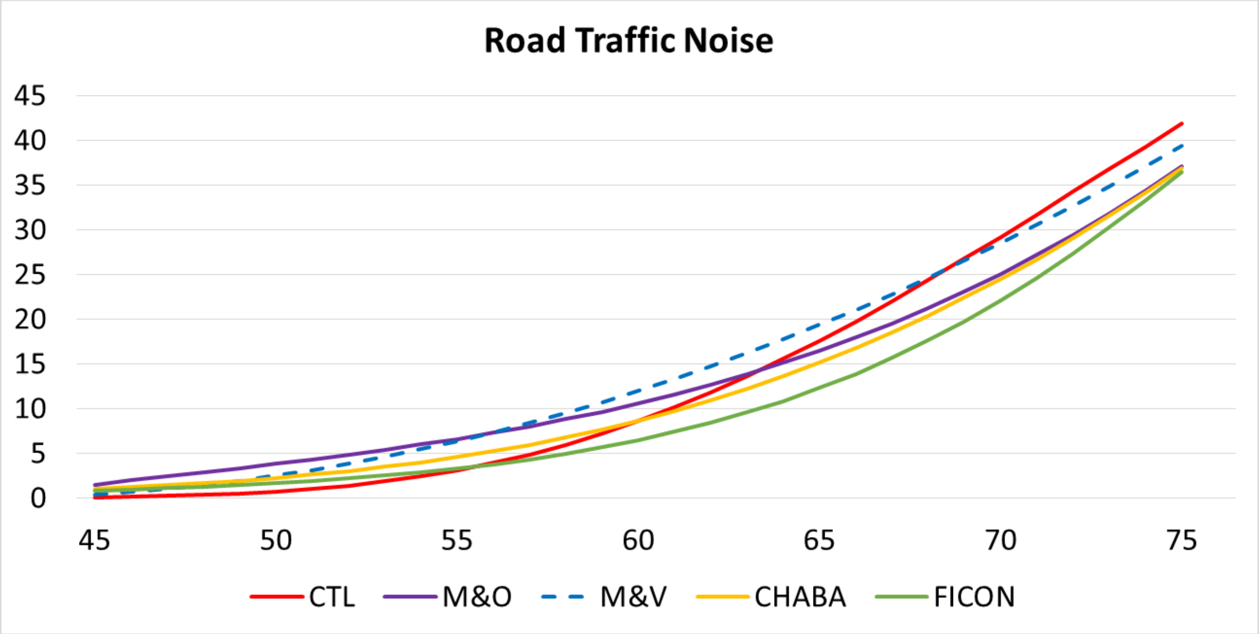

Figure 2A: 5 curves for determining %HA for road traffic noise

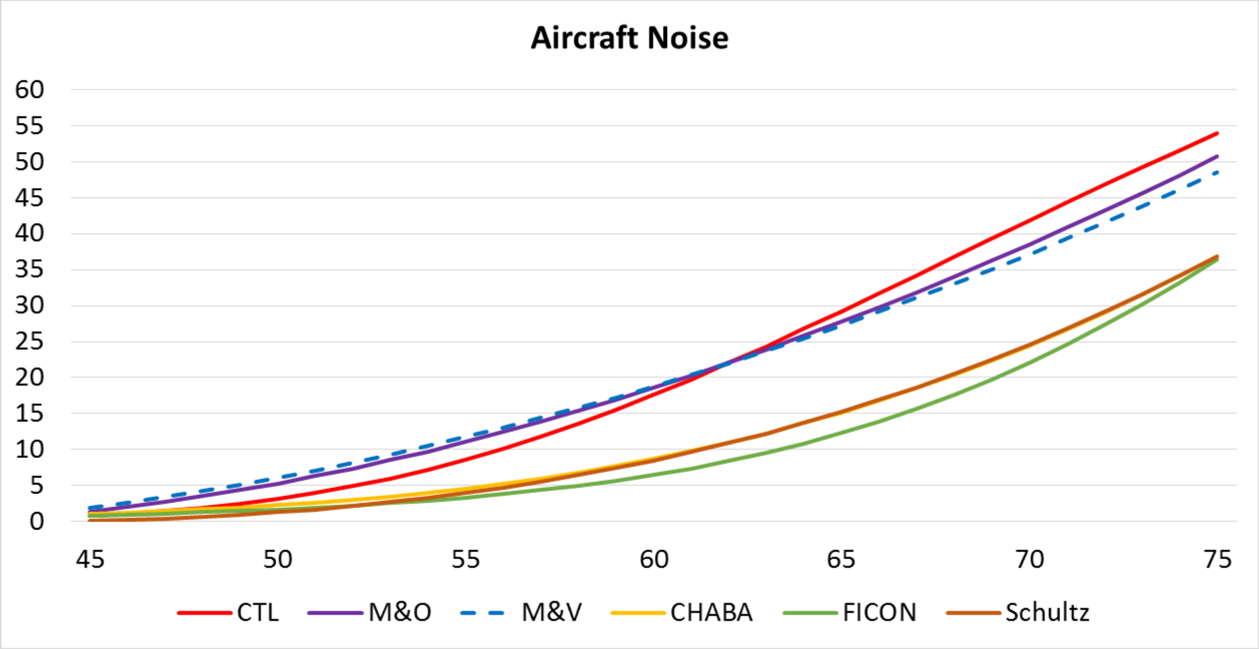

Figure 2B: 6 curves for determining %HA for aircraft noise

5.WHAT IS THE ACCEPTABLE LIMIT FOR PERCENT HIGHLY ANNOYED (%HA)?

A. ESTABLISHING A FUNCTION FOR %HA vs DNL

Since the purpose of this report is to establish data and relations for the selection of a wind turbine noise criterion. In this section, four independent methods are given with which to establish a relation by which to judge wind turbine noise annoyance. During at least the last several years, it has been common to use road traffic noise as the "yardstick" by which other noises are measured. Miedema and Vos (1997), Miedema and Oudshoorn (2003), Fidell *et al.* and Schomer *et al.*, as well as ISO 1996-1 all use road traffic noise for this purpose.

In 2005, Schomer examined the metrics and criterions used by nearly every federal agency and board, by recommendations in national standards, and by international recommendations such as those made by the World Health Organization. These, and multiple other sources agree to 55 DNL as an acceptable criterion for road traffic noise. Therefore, we will use 55 DNL as our intermediate criterion. The term "intermediate" is used because the real issue is annoyance and not decibels. It is very common to relate %HA to decibels, but it is almost always decibels that are measured and not annoyance. For a DNL of 55 dB, 4 different estimates of %HA were found in the literature. CTL equates 55 DNL with about 3% HA, Miedema and Oudshoorn equates 55 DNL with about 7% HA, for road traffic and aircraft noise separately, and CHABA predicts about 5% for a DNL of 55, for both air and road traffic combined. Herein, we will be using the average of these four estimates, which is 5%.

B. CHOOSING A CRITERIA

1. The first method, the method that is dependent on %HA, relates the data from Health Canada to the 5% value established above. Michaud *et al.* (2013) writes that "Consistent with Pedersen et al. (2009), the increase in wind turbine annoyance was clearly evident when moving from [30–35) dB to [35–40) dB, where the prevalence of wind turbine annoyance increased from 1% to 10%. This continued to increase to 13.7% for areas where WTN levels were [40–46] dB." Michaud relates 3 different values for %HA values with 3 corresponding decibel levels: 1%HA is related to 32.5 dB(A), and 10%HA is related to 37.5 dB(A). Therefore, 5%HA would be related to a value between 32.5 and 37.5 dB(A), most likely around 35 dB(A). With this method, a 5%HA criterion is related to 35 dB(A). A more conservative criterion is given by the doubling of the %HA from 5 to 10%. For this second %HA limit, the corresponding dB(A) level is 37.5 dB(A).

2. The second method compares CTL for road traffic noise to CTL for wind turbine noise. The average CTL for road traffic noise (Schomer *et al.* 2012) is 78.3 dB. In comparison, the average CTL for wind turbine noise is 62 dB. So, a 16 dB difference is found between wind turbine noise and the traffic noise "yardstick." To complete this comparison, one must have a value for an acceptable DNL for road traffic noise. Here, a range of DNL is considered: 55-60 dB. Subtracting 16 yields a range of 39-44 dB for wind turbine noise. As per section II-B above, 6-7 dB is subtracted from DNL in order to calculate Leq. This subtraction yields a range of 32-38 dB as a limit for wind turbine noise.

3. A third method to develop a criterion is to directly apply ANSI S12.9 Parts 4 and 5. Part 5 recommends a DNL of 55 dB for residential areas as a limit based on the start of impact. Part 4 recommends a 10 dB

penalty on the limits for quiet rural areas. Most wind farms are built in quiet rural areas, so this penalty is applicable in this case. In a quiet rural area, the DNL limit becomes 45 dB. But this is DNL, to get to Leq we must subtract 6-7 dB, so that the recommendation becomes an Leq of 38-39 dB.

4. Data published by the Minnesota Department of Commerce, shown in Figure 1, give noise limits for sensitive rural areas and non-sensitive areas. As an example of land use designations, wind turbine noise limits in South Australia are based on the highest level applicable between: rural areas at 35 dB(A), non-rural areas at 40 dB(A), or 5 dB(A) above background measured as L90. The average value of the noise limits for sensitive areas given by the Minnesota report is about 36 dB(A).

6. ANALYSIS AND CONCLUSIONS

Four independent data sources are used to create four estimates of an acceptable 24-hour A-weighted Leq criterion for wind turbine noise. Two methods use 5% highly annoyed as the estimated start of impact for a receiving person. The remaining methods examine both adjustments to a recommended DNL indicating start of impact, and an analysis of existing wind turbine noise limits. The four estimates of a criterion are listed below:

1. 5% HA is shown to be a very approximate average to a criterion for %HA. In order to be conservative, the range from 5 to 10% is considered herein. Applying a 5% HA value to the Health Canada data gives a limit between 32.5 dB and 37.5 dB, or about 35 dB(A). Applying a 10% HA value to the Health Canada data gives a limit of 37.5 dB(A) (Michaud *et al.* 2016b).

2. A 16 dB difference is found between the CTL for road traffic noise and WTN, and if the metric is Leq, then the difference between WTN and Leq is another 6-7 dB, for a total of 22-23 dB difference. Comparing the CTL for wind turbine noise to the CTL for road traffic at the lower limit of 55 DNL for road traffic suggests a limit of 32-33 dB(A). Comparing the CTL for wind turbine noise to the CTL for road traffic at the upper limit of 60 DNL for road traffic suggests a limit of 37-38 dB(A).

3. Applying ANSI S12.9 Parts 4 and 6 to determine the level at which impact will start in a quiet, rural area gives a limit of 38-39 dB(A).

4. The average of existing worldwide limits found in the Minnesota Department of Commerce report for sensitive areas is about 36 dB.

As applicable, Table 2 lists the minimum, average, and maximum Leq criteria for wind turbine noise for each of the four methods above:

	Minimum (dB)	Average (dB)	Maximum (dB)
1-%HA		35	37.5
2-CTL	32		38
3-ANSI		38	39
4-MN DoC		36	
AVERAGE	**32**	**36.3**	**38.2**

Table 2: Minimum, average, and maximum Leq criteria

The average of the top-end values is about 38 dB(A) and the average of the middle values is about 36 dB(A). The minimum level, 32 dB, is not emphasized. These four sets of independent data result in criteria recommendations that are remarkably close to one another, lending support to a 24-hour A-weighted Leq wind turbine noise criterion in or around the range of 36-38 dB(A).

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A theory to explain some physiological effects of the infrasonic emissions at some wind farm sites

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(Received 20 November 2013; revised 1 October 2014; accepted 4 February 2015)

For at least four decades, there have been reports in scientific literature of people experiencing motion sickness-like symptoms attributed to low-frequency sound and infrasound. In the last several years, there have been an increasing number of such reports with respect to wind turbines; this corresponds to wind turbines becoming more prevalent. A study in Shirley, WI, has led to interesting findings that include: (1) To induce major effects, it appears that the source must be at a very low frequency, about 0.8 Hz and below with maximum effects at about 0.2 Hz; (2) the largest, newest wind turbines are moving down in frequency into this range; (3) the symptoms of motion sickness and wind turbine acoustic emissions "sickness" are very similar; (4) and it appears that the same organs in the inner ear, the otoliths may be central to both conditions. Given that the same organs may produce the same symptoms, one explanation is that the wind turbine acoustic emissions may, in fact, induce motion sickness in those prone to this affliction.

[http://dx.doi.org/10.1121/1.4913775]

[BSF] Pages: 1356–1365

I. INTRODUCTION

For at least four decades there have been reports in the scientific literature of people experiencing motion sickness-like symptoms attributed to low-frequency sound and infrasound. For example, Dawson (1982) makes the following points:

"Apart from the matter of acoustic fatigue in buildings and other structures, the main problem arising from excessive low frequency noise concerns people who can be disturbed, annoyed, made wretched or ill by acoustic insult to a degree which can be disruptive on a local scale and which nationally produces significant economic and social penalties."

He adds that: "[With] low frequency noise some people can be distressed to an extreme degree while others remain quite unaffected."

"Once a person has displayed some sensitivity to low frequency noise, further exposure lowers the sensitivity threshold."

"Any sensitivity is exacerbated by the presence of other stresses. The low frequency sensitivity syndrome includes: Feelings of irritation, unease, stress, undue fatigue, headache, nausea, vomiting, heart palpitations, disorientation, swooning, prostration."

Fifteen years later, Tesarz *et al.* (1997) reports much the same scenario: "In case studies of persons sensitive to low frequency noise, symptoms such as pressure on the eardrum or a pulsating feeling on the eardrum have been the most consistent result. Other symptoms that have been reported in both field and experimental studies are tiredness, irritation and uneasiness, difficulties to concentrate, headache, nausea and dizziness…."

Adopting the conclusions of Tesarz, Annex C, Clause C.1 of ISO 1996-1 (2003) states "…that the perception and the effects of sounds differ considerably at low frequencies as compared to mid or high frequencies." The text goes on to list six reasons for these differences. Two of these reasons are: (1) "perception of sounds as pulsations and fluctuations," and (2) "complaints about feelings of ear pressure." These are the same two effects as those listed in the preceding text by Tesarz as "most consistent."

Now these same problems are appearing in the vicinity of wind farms, and as in 1982 and earlier, nobody understands how these problems arise; nor is it understood why only a fraction of the population is affected.

The purpose of this paper is to provide a foundation upon which the reported effects of infrasound from wind turbines may be investigated. This paper presents a theory upon which needed investigations can go forward. The Appendix outlines some elements of a research statement.

II. DATA FROM A PROBLEM SITE

A. Observations from people affected by the installation of wind turbines

One wind farm that is experiencing these problems is in Shirley, WI. Here three families have abandoned their homes

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[a)] Author to whom correspondence should be addressed. Electronic mail: schomer@SchomerAndAssociates.com because family members who became ill after installation of the turbines could not acclimate to the situation.[1] Because of these conditions in Shirley, a study was conducted with the proposed test plan calling for the wind farm owner to cooperate fully in supplying operational data and by turning off the units for short intervals so the true ON/OFF impact of turbine emissions could be documented. The owner declined this request citing the cost burden of lost generation from the eight turbines at the Shirley site.

Four acoustical consulting firms cooperated to jointly conduct this study: (1) Channel Islands Acoustics (ChIA), (2) Hessler Associates, Inc., (3) Rand Acoustics, and (4) Schomer and Associates, Inc.

This study was conducted during a 3-day period in December, 2012. The first task accomplished was to meet with residents having problems with the wind turbine acoustic emissions including members of the three families who had abandoned their homes. These discussions with the residents yielded the following observations:

(1) At most locations where these various symptoms occurred, the wind turbines were generally not audible. That is, these problematic symptoms are devoid of noise problems and concomitant noise annoyance issues. The wind turbines could only be heard distinctly at one of the three residences examined, and they could not even be heard indoors at this one residence during high wind conditions.
(2) Some residents reported that they could sense when the turbines turned on and off; this was independent of hearing or seeing the turbines. This assertion by the residents is readily testable, and a plan to test this assertion is briefly summarized in the Appendix.
(3) The residents reported "bad spots" in their homes but pointed out that these locations were as likely to be "bad" because of the time they spent at those locations as because of the "acoustic" (inaudible) environment. The residents did not report large changes from one part of their residences to another.
(4) The residents reported little or no change to the effects based on any directional factors. Effects were unchanged by the orientation of the rotor with respect to the house; the house could be upwind, downwind, or crosswind of the source.
(5) Many of the residents reported motion sickness like symptoms as adverse effects associated with the wind turbines.

Two of the major implications of these five findings are: (1) Because these residents largely report wind turbines as inaudible, it seems that suggestions some have made that these conditions are being caused by extreme annoyance can be ruled out and (2) the lack of change with orientation of the turbine with respect to the house and the lack of change with position in the house suggest that we are dealing with very low frequencies; frequencies such that the wavelength is a large fraction of the wind-turbine diameter (i.e., about 3 Hz or lower).

It should be mentioned that there are about 120 residences within about 5000 ft of the closest turbine; this suggests that there are about 275 residents. Of these 275 residents, 50 have described adverse effects that they have experienced after the introduction of the wind turbines. It is not known how many of the 120 residences are "participating," but most agreements for participating residences include some form of confidentiality and non-complaint clauses.[2]

The most common complaints are feelings of pressure and pulsations in the ears. And this is very much in accordance with ISO 1996-1 (2003) where, as discussed in the preceding text, these two factors are listed as the most common effects of low-frequency noise. However, in this paper, we are concentrating on sea-sickness like symptoms.

B. Physical measurements

Figure 1 is an aerial photo of the Shirley wind farm. This figure shows the positions of five of the eight wind turbines that make up this site, Nordex N-100 s, and the position of the three abandoned residences. Primary measurements were made at residences 1–3 on consecutive days.

Bruce Walker of Channel Island Acoustics employed a custom designed multi-channel data acquisition system to measure sound pressure in the time domain at a sampling rate of 4000/s where all signals are collected under the same clock. The system is calibrated to be accurate from 0.1 Hz thru 10 000 Hz. Measurements were made both inside and outside the house to gather sufficient data for applying advanced signal processing techniques.

George and David Hessler of Hessler Associates, Inc., employed four off-the-shelf type 1 precision sound level meter/frequency analyzers with a rated accuracy of ±1 dB from 5 to 10 000 Hz. Two of the meters were used as continuous monitors to record statistical metrics for every 10-min interval over the 3-day period.

Robert Rand of Rand Acoustics observed measurements and documented neighbor reports and physiological effects including nausea, dizziness, and headache. He used a highly accurate microbarograph to detect infrasonic pressure modulations from wind turbine to residences.

Paul Schomer of Schomer and Associates, Inc., observed all measurements. Among other things the following observations are made based on the results of the physical measurements. In particular, these observations are based upon the coherence calculations by Bruce Walker. Figure 2 shows the coherence between the outdoor ground plane microphone and four indoor spaces at residence 2: The living room, the master bedroom, behind the kitchen, and in the basement. The data collected at residence 2 were measured with only 58% of turbine power, although the wind conditions were optimal for turbine operation, and the power was much less than 58% during the measurement periods at R1 and R3.

It is inferred from the residents' observations that the important effects result from very low frequency infrasound of about 3 Hz or lower. We can test this assertion with the data collected at the three residences at Shirley. Only residence 2 was tested during a time when significant power was being generated, so it is the only source of data used herein. Figure 2 shows the coherence between the outdoor ground plane microphone and the four indoor spaces listed above

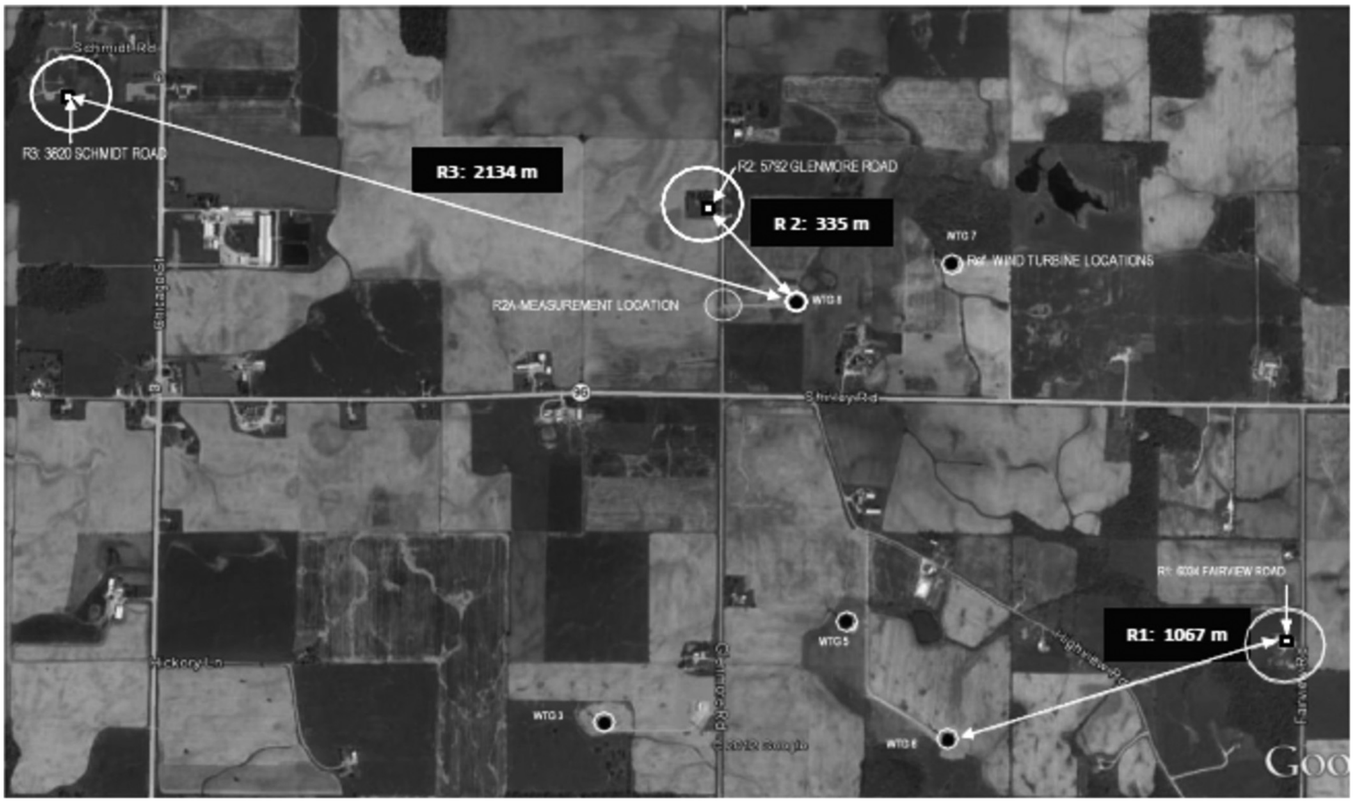

FIG. 1. Aerial photograph of the site showing the three residences and the five closest wind turbines.

for the frequency range from 0.5 to 7 Hz. All of the four spaces exhibit coherence at 0.7, 1.4, 2.1, 2.8, and 3.5 Hz, and in this range, there is no coherence indicated except for these five frequencies. The basement continues, with coherence exhibited at these higher harmonically related frequencies of 4.2, 4.9, 5.6, 6.3, and 7 Hz. The three indoor microphones situated on the first floor exhibit only random zones of high and low coherence as a function of frequency but not so as to correspond to other microphones in the house. That is, above 5 Hz the three indoor microphones exhibit only random periods of coherence, and above 7 Hz the basement microphone exhibits only random periods of coherence. But all four microphones are lock step together in their coherence with the outdoor microphone below about 4 Hz.

As an analysis that is complementary to the coherence plots of Fig. 2, Fig. 3 shows spectral plots of data collected at residence 2. As in the coherence plots, one can see the first several harmonics of the wind-turbine blade-passage frequency, 0.7 Hz, and nothing notable above about 7 Hz. Two channels of measurement are shown on Fig. 3, the outside, ground plane microphone (upper curve), and the indoor microphone in the living room (lower curve). Note that the pressures that result from the acoustic emissions of the wind turbines, when measured indoors, keep growing as the frequency goes lower because the entire house is behaving like a closed cavity.

Based on this analysis of the spectral and coherence data, we conclude that the only wind turbine-related data

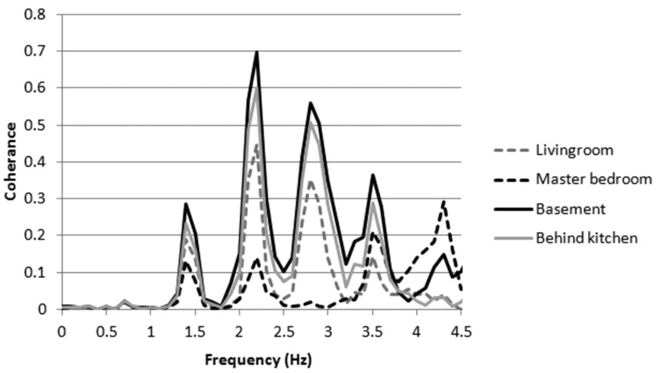

FIG. 2. Coherence between the each of the four indicated rooms with the outdoor-ground plane microphone.

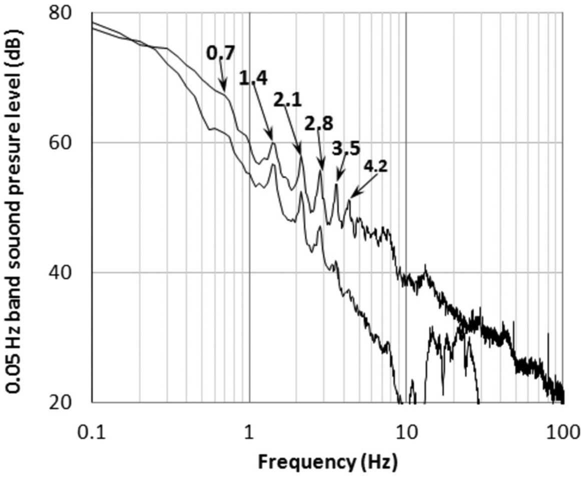

FIG. 3. Spectral plot of the ground-plain outdoor microphone data (upper trace) and indoor data measured in the living room of Residence 2 (lower trace).

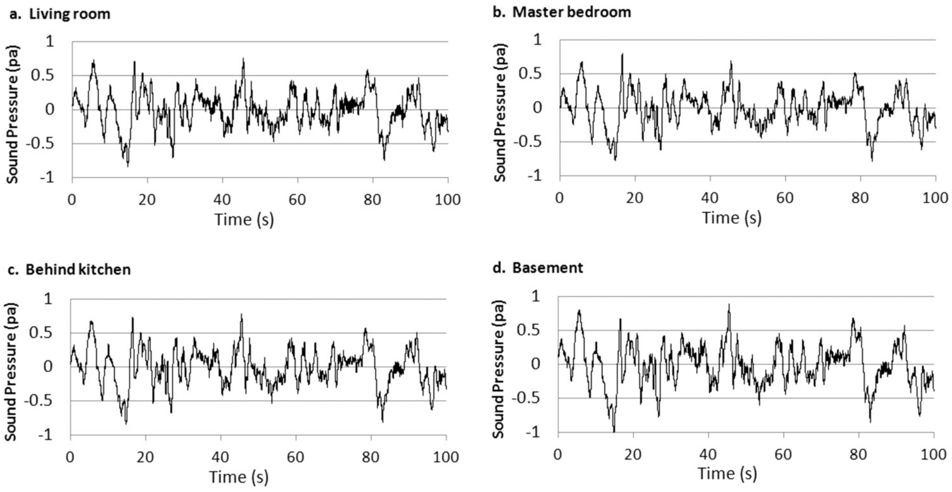

FIG. 4. Sound pressure versus time for of the data collected at the four indoor measurement locations indicated in Fig. 2 and for the first minute of data from the data set used for Fig. 2. Note that the sound pressure versus time is very similar for all indoor locations.

evident in the measurements at residence 2 are the very low frequencies ranging from the blade passage frequency of 0.7 Hz to up to about 7 Hz. This conclusion is consistent with the residents' reports that the effects were similar from one space to another but a little to somewhat improved in the basement, the effects were independent of the direction of the rotor and generally not related to audible sound.

Figure 4 shows the sound pressure level for the first minute of the 10 min represented on Fig. 2, above. This figure, which is sensitive to the lowest frequencies, shows that at these very low frequencies, the sound pressure levels in all four spaces are quite similar. The small changes from different positions in the house also suggests that the house is small compared to the wavelength so that the insides of the house are acting like a closed cavity with uniform pressure throughout being driven by very low-frequency infrasound.

The measurements support the hypothesis developed in the preceding text that the primary frequencies are very low, in the range of several tenths of a hertz up to several hertz. The coherence analysis shows that only the very low frequencies appear throughout the house and are clearly related to the blade passage frequency of the turbine. As Fig. 4 shows, the house is acting like a cavity and indeed at 5 Hz and below, where the wavelength is 60 m or greater, the house is small compared to the wavelength.

While we would have liked to have been able to draw conclusions on measurements at all three sites, that was not possible because the energy company was not generating much power during the measurements of R1 and R3, and even just over 50% during the measurements at R2.[3]

III. THE MOTION SICKNESS HYPOTHESIS

A. The Navy's nauseogenic region

As a starting point we consider a paper by Kennedy *et al.* (1987) entitled: "Motion sickness symptoms and postural changes following flights in motion-based flight trainers." This paper was motivated by Navy pilots becoming ill from using flight simulators. The problems encountered by the Navy pilots appear to be similar to those reported by about five of the Shirley residents. This 1987 paper focused on whether the accelerations in a simulator might cause symptoms similar to those caused by motion sickness or seasickness. Figure 5 (Fig. 1 from the reference) shows the advent of motion sickness in relation to frequency, acceleration level and duration of exposure. To develop these data, subjects were exposed to various frequencies, acceleration levels, and exposure durations, and the Motion Sickness Incidence (MSI) was developed as the percentage of subjects who vomited. Figure 5 shows two delineated regions. The lower region is for an MSI of 10%. The top end of this region is for an exposure duration of 30 min and the bottom end is for 8 hr of exposure. The upper delineated region has the same duration limits but is for an MSI of 50%.

What is important here is the range encompassed by the delineated regions of Fig. 5. Essentially, this nauseogenic condition appears to occur primarily below 1 Hz. Note that the Navy criteria are for acceleration, while in Shirley we are dealing with pressures in a closed cavity, the house. The similarity between force on the vestibular components of the inner ear from acceleration and pressure on these from being in a closed cavity suggests that the mechanisms and frequencies governing the nauseogenic region might be similar for both pressure and acceleration, and much of this paper is concerned with showing the plausibility of the ear responding in like fashion to accelerations of a moving vehicle and acoustic pressures at these same infrasonic frequencies (e.g., 0.7 Hz).

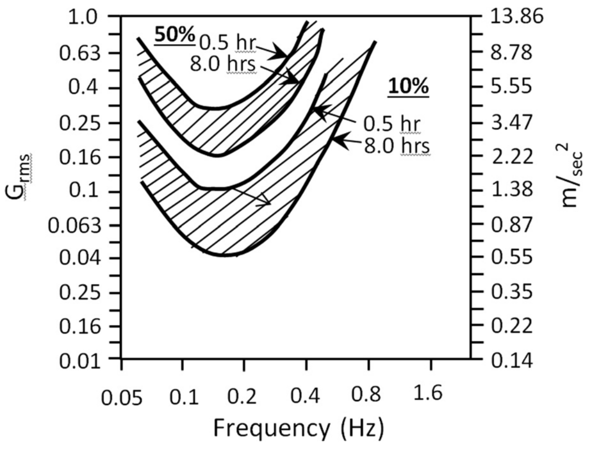

FIG. 5. The nauseogenic region as developed by the U.S. Navy (after Kennedy *et al.*, 1987).

As the generated electric power of a wind turbine doubles, the sound power doubles and the blade passage frequency decreases by about 1/3 of an octave (Møller and Pedersen, 2011).[4] The wind turbines at Shirley have a blade passage frequency of about 0.7 Hz. This suggests that a wind turbine producing 1 MW would have a blade passage frequency of about 0.9 Hz, and on Fig. 5, a change from 0.7 to 0.9 Hz requires a doubling of the acceleration for the same level of response. Thus it is very possible that this nauseogenic condition has not appeared frequently heretofore because older wind farms were built with smaller wind turbines. However, the 2.5 MW, 0.7 Hz wind turbines clearly have moved well into the nauseogenic frequency range.

B. Motion sickness like symptoms and their implications

We systematically listed the symptoms of low frequency noise, as given by the two papers cited in the preceding text (Dawson, 1982; Tesarz *et al*., 1997), and on the same basis, we listed the symptoms of sea-sickness, using two journal papers (Stevens and Parsons, 2002; Bittner and Guignard, 1988) and the symptoms listed by the National Health Service (2014) and C-Health (2013). Table I compares the various frequencies of the indicated symptoms of seasickness and low-frequency infrasound sickness from this published literature. The two sets of symptoms are strikingly similar.

Motion sickness, or kinetosis, is generally related to the vestibular, visual, and somatosensory systems (cf. Griffin, 1990). A common theory of the cause of kinetosis is that of sensory conflict: The information received from two or more sensory systems conflict (e.g., visual inputs in a closed room and vestibular inputs from a rolling boat) producing symptoms similar to that of ingesting a poisonous substance. The result is an evolutionary protective response to rid the body of a harmful foreign substance. Thus motion sickness is not really a sickness but rather is a natural reaction to unusual input information.

At the start of this analysis, the working hypothesis was that wind turbine noise somehow, because of the nauseogenic regions similarity, created symptoms that were similar to those of motion sickness. We now have a much simpler hypothesis—just as some people experience motion sickness when watching movies and videos, wind-turbine acoustic emissions trigger motion sickness in those who are susceptible; it is another form of *pseudo-kinetosis*.

TABLE I. Percent of references citing symptom indicated.[5]

	Composite of four sea sickness studies or information papers	Composite of two low frequency "sound" sickness studies
Not feeling well	100	100
Dizziness	100	100
Headache	100	100
Nausea and vomiting	100	100
Sleepiness, drowsiness, and sleep disturbance	75	100
Fatigue and tiredness	75	100
Difficulty thinking	25	50
Irritation	25	100
Sweating	100	0
Pale	75	0

At Shirley, of the 50 people who reported symptoms after the introduction of wind turbines to the area, 5 of those 50 people reported symptoms similar to motion sickness. We simply have no information on other area residents, except for these 50, and do not know how many of the other residents are participating.[3] Based on the sample of 5 of 50, we can say that the incidence of motion sickness symptoms at Shirley is 10% or less, a figure that is clearly in line with the expected percentage of those in the general population affected by motion sickness.[6] In fact, Montavit (2014) indicates that "about 5% to 10% of the population is extremely sensitive to motion sickness; 5% to 15% are relatively insensitive; and about 75% are only subject to it to a 'normal,' i.e., limited degree."

In our meeting with affected residents discussed in the preceding text, it was stated that each person affected by the wind farm noise in the form of motion sickness symptoms was also motion sickness sensitive. The same is true for Rob Rand and Steve Ambrose, who are two acoustical researchers who have themselves reported suffering strong symptoms from low frequency wind-turbine emissions.

As noted in the preceding text, inconsistent proprioception, accelerations, and visual cues may not be resolved and cause a defensive emetic response. For example, during a car trip, nerves and muscle receptors do not register any movement because the body itself is sitting still. The eyes, on the other hand, send the brain a message of fast motion. The equilibrium organ in the inner ear delivers information of curves, acceleration, and/or ascents that contradict the messages from the other two sources. This contradictory flood of impulses and information overburdens a healthy sense of equilibrium that the brain, in turn, interprets as a danger situation. It then releases stress hormones, which in turn create symptoms of dizziness and nausea.

So to induce a sense of motion where none exists and thereby create the sensory conflict that is requisite to induce motion sickness requires that the acoustic signal cause the vestibular system to "tell the brain" it is accelerating when the ocular system is telling the brain there is no motion.

IV. EXCITATION OF THE OTOLITH

A. The middle ear and inner ear

As shown on Fig. 5, the Navy criteria for the likelihood of sea sickness are functions of three factors: (1) Duration of exposure to the motion, (2), amplitude of the acceleration, and (3) frequency of the acceleration. Moreover, because the blade passage frequency has been decreasing and the acoustic power has been increasing as the turbines get larger, one can imagine a future with greater, more frequent problems like those in Shirley (Møller and Pedersen, 2011) (footnote 4). There is one main question that greatly affects the likelihood of this eventuality. This main question relates to the fact that the Navy criteria are based on acceleration, while the wind-turbine acoustic emissions are very low frequency acoustic pressure waves.

In the following, we show only that it appears that an acoustic wave at 0.5–0.7 Hz can generate a similar response as the signal generated by acceleration at 0.5–0.7 Hz. This discussion analyzes the linear motion sensing function of the ear and explains how the ear could respond to wind turbine emissions. We are concerned primarily with the inner ear.

Figure 6 shows just the inner ear, which contains the cochlea, the organ that transforms the sound wave into locally acting vibration at frequencies ranging from about 10 Hz to about 20 kHz (Obrist, 2011). The inner ear also contains the vestibular system, which controls and facilitates balance and motion. The system of semicircular canals has evolved to be able to sense rotational movements of the head while remaining rather insensitive to forces arising either from translational acceleration of the body or gravity: The cupulae normally have a similar specific gravity to that of the endolymph. The vestibular perception of translational forces originates normally from sensory systems (maculae) located within the utricle and saccule.

As shown in Fig. 7, the classical description for the maculae are flat gelatinous masses (otollithic membrane) covered with minute crystals (otoconia) connected to an area of the utricle and saccule by cells, including hair cells. A suitably oriented translational force will cause the mass to exert a shear force, resulting in a variation in the firing rate of the hair cells. The maculae cover an area of a few square millimeters. They are located on the floor and lateral wall of the utricle and, in an orthogonal plane, on the anterior wall of the saccule (Griffin, 1990).

These six inner ear organs, the cochlea, the three SCCs, the saccule, and the utricle, open into the inner space, the vestibule. The inner ear is divided into distinct fluid-filled chambers containing perilymph and endolymph. A hard bone and fluid (perilymph) surrounds the scala media, which are filled with endolymph, and the only openings to the "outside" are two windows, the round window, which separates the air-filled middle ear from the fluid-filled inner ear by a thin membrane, and the oval window, which connects to the stapes, and also separates the inner ear from the middle ear by means of a thin (round window) membrane (Obrist, 2011).

As the acoustic pressure impinges on the tympanic membrane, it travels through the middle ear and into and through the inner ear from the oval window to the round window. Like a transformer in an electric circuit, the middle ear increases the pressure by 29 dB with a corresponding decrease in velocity. This transformer matches the impedance of air to the impedance of the inner ear fluids. At high frequencies, the tympanic membrane develops modes that affect the transmission of sound across the middle ear. Low frequencies do not create these vibration modes and the membrane vibrates as a "plate." The round window is compliant and responds to the pressure wave that travels up the scala vestibuli and down the scala tympani to create shear forces in the cochlea. These two "tunnels" surround the basilar membrane. Additionally, there is a communication between the scala vestibuli and the vestibular system by means of which acoustic pressure might be transmitted to the otoliths.

B. Classical model of the otolith

We have shown there is a plausible path for the infrasound pressures to reach the inner ear and in particular the otoliths. The classical model of the otolith is shown pictorially in Fig. 7. The otoconial layer is a rather dense, firmer layer of the otolith. It thickens at the surface. The otoconial layer gets its density from embedded calcium carbonate crystals (otoconia). The otoconial layer creates an inertial force when accelerated owing to its mass. This force is transferred to the gel layer (cupula), which then bends the hair cells causing them to transmit signals to the brain. Figure 7 shows in a simple way how the mass in the otoconial layer creates an inertial force that results in shear forces in the cupula and bending of the hair cells coupled into the cupula. So the fundamental measurement by the otolith is the inertial force of the otoconial layer (Grant and Best, 1986); the otolith is measuring force.

C. Calculations of forces acting on the otolith

In this section, we approximate and compare two potential forces acting on the otoliths: (1) Inertial force to accelerations and (2) forces due to the instantaneous pressure in an acoustic wave.

Although the more complete solution for modeling the motion of the otolith is given by a parabolic partial differential equation (Grant and Best, 1986), the frequency response of the otoliths is flat from DC to about 10 Hz (McGrath, 2003), the

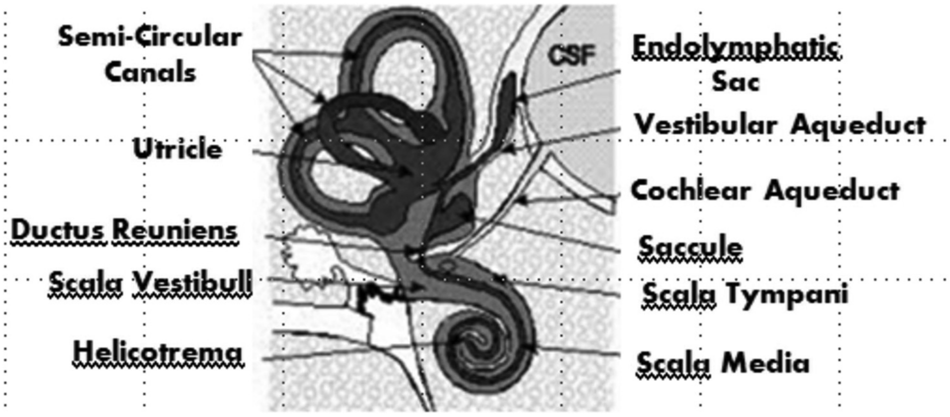

FIG. 6. The inner ear (after Salt, unpublished data).

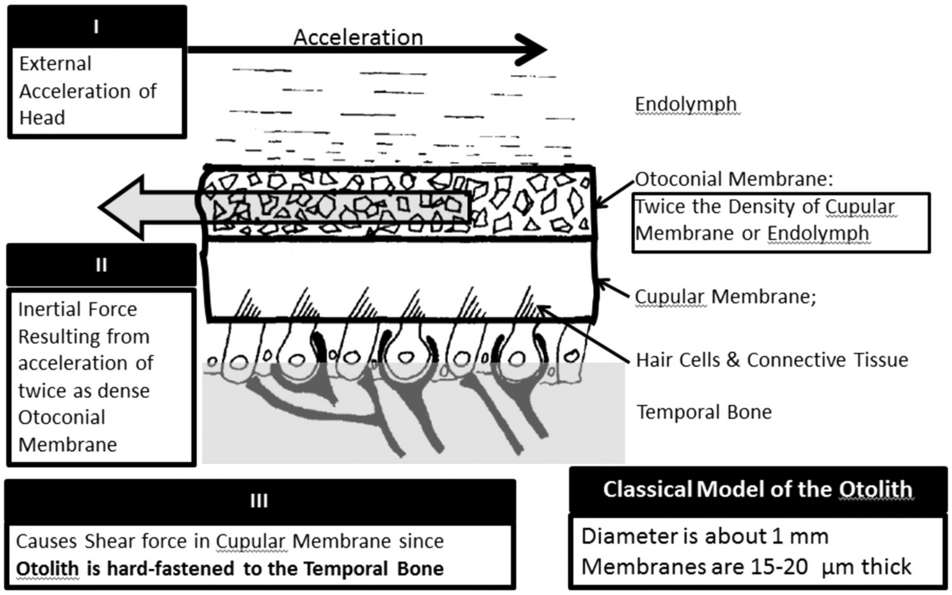

FIG. 7. Schematic sectional drawing of the classical model for the otolith.

position of the poles in the response being functions of assumptions for values of certain parameters describing physical attributes of the layers and their constituents. For an order of magnitude calculation, we simply consider $F = \text{ma}$, where the acceleration is precisely the acceleration of the head, and the mass is the differential density of the otoconial layer minus the density of the surrounding fluid and the cupular membrane times the volume of the otoconial layer. Although calcium carbonate has a density of 2.7 g/cm^3, the density of the otoconial layer is taken to be 2 g/cm^3 because it is a combination of the dense calcium carbonate and the less dense gel material. The density of the cupular membrane and of the endolymph, which has properties given as being similar to water, is taken as 1 g/cm^3, so the differential density is 1 g/cm^3 or 1000 kg/m^3. As can be seen in the classical model of the otoliths (Fig. 7), they are approximated as round and their diameter is about 1 mm. The thickness of the otoconial layer has been given as 15–20 μm (Grant and Best, 1986). Therefore we calculate: the $\text{mass} = \text{density} * \text{height} * \text{top surface area}$ or, $\text{mass(kg)} = 10^3\ (\text{kg/m}^3) * 18 * 10^{-6}\ \text{m} * \pi * 0.5 * 10^{-3} * \text{m} * 0.5 * 10^{-3} * \text{m} = 18 * \pi/4 * 10^{-9} \approx 1.4 * 10^{-8}\,\text{kg}$, where $\text{density} = 10^3\ (\text{kg/m}^3)$, $\text{height} = 18 * 10^{-6}$ m, and top surface $\text{area} = \pi * 0.5 * 10^{-3} * \text{m} * 0.5 * 10^{-3} * \text{m}$. With reference to Fig. 7, we take the acceleration to be 5 m/s^2, so the acceleration force,

$$F_{\text{accel}} = 7 * 10^{-8}\text{N}.$$

In terms of the pressure of an acoustic wave, we take the sound pressure level (SPL) to be 54 dB, which corresponds to 0.01 Pa, and because of the "transformer" function of the middle ear, we assume a 29 dB gain in pressure. Therefore the acoustic force, $F_{\text{acous}} = 28 * 0.01 * \pi/4 * 10^{-6}\ \text{N} \approx 22 * 10^{-8}\ \text{N}$.

D. Excitation of the otoliths

More recent research tends to confirm the model presented in the preceding text for the excitation of the saccule. It is shaped something like an elongated hemi-sphere with the base of the hemi-sphere rigidly attached to the temporal bone and the otoconial layer on the top where under the force of acceleration shear forces can be set up in the cupula. However, there is radically new information about the utricle. Uzun-Coruhlu *et al.* (2007) have used x-ray microtomography and a method of contrast enhancement to produce data revealing "that the saccular maculae are closely attached to the curved bony surface of the temporal bone as traditionally believed, but the utricular macula is attached to the temporal bone only at the anterior region of the macula" (see Fig. 8). This changes the model for excitation of the utricular macula. According to Uzun-Coruhlu *et al.* in the classical view of the utricular macula

"…the sub-surface of utricular macula is implied (if not actually stated) to be rigid; these models do not accommodate the "floating" utricular macula which we have shown and which is consistent with other anatomical evidence (e.g. Schuknecht, 1974). Since the hair cell receptors on the utricular macula are stimulated by forces there would be a major difference in modeling the sensory transduction of the macula to such forces if the forces acted on a tenuously supported flexible membrane or acted on a membrane which is rigidly attached to bone. As an example, modeling the magnitude of utricular hair cell displacement to an increased dorso-ventral g-load during centrifugation will be quite different if the whole membrane is deflected by the g-load or if it remains fixed in place. The latter rigid attachment has been explicitly or tacitly assumed, whereas our results show the macula is not rigidly attached to bone."

"The key information which is now required for realistic modeling of utricular transduction is information about the flexibility of the utricular membrane to determine the extent to which it would be deflected by such forces."

Essentially, Uzun-Coruhlu *et al.* are saying that the excitation of the otolith in the utricle depends on the flexibility of the utricular macula. Because the macula is not rigidly attached to the temporal bone, the classical model (Fig. 7) for excitation of the otolith by acceleration does not work. One way for inertial forces on the otolith to create bending forces is if the stiffness of the utricular membrane varies with position. Then inertial forces on the otolith will make

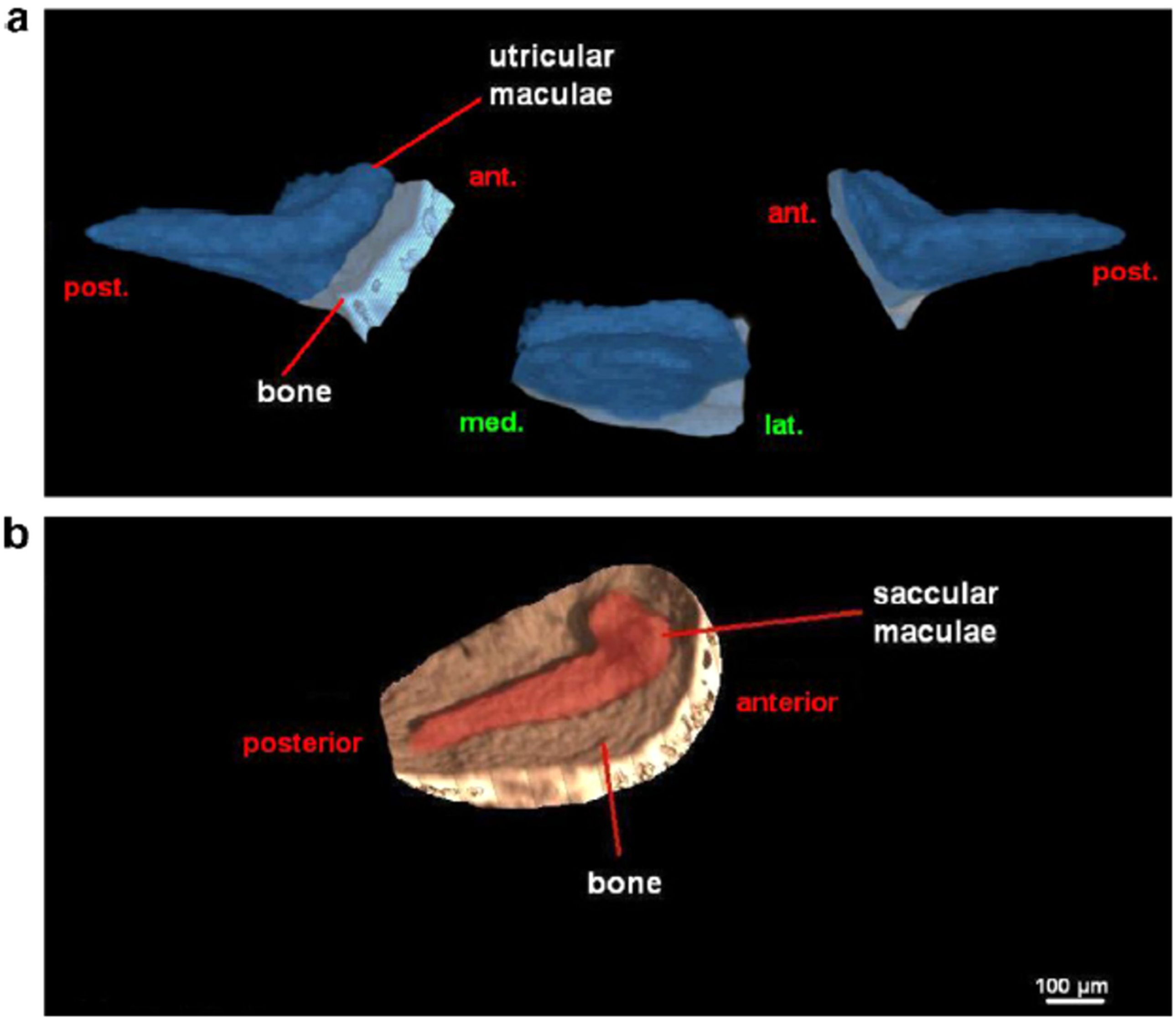

FIG. 8. (Color online) Artist rendered three-dimensional images of the utricular and the saccular maculae of a guinea pig (from Uzun-Coruhlu *et al.*, 2007).

the otolith "bulge" where it is less stiff and contract where it is stiffer, producing bending forces that will trigger the hair cells. Precisely the same thing will happen if the force is externally applied through the endolymph as when the force is internally applied through the otoconial layer. In this model, if there is external force on the utricle, it will expand where it is less stiff and contract where it is stiffer. In particular, the acoustic pressure that reaches the otolith through the eardrum and middle ear pathway described earlier should cause the utricular macula to signal the brain in virtually identical fashion to signals generated by inertial forces, i.e., forces generated by acceleration of the head. That is, the utricular macula should respond in like fashion to acoustic pressure fluctuations and direct acceleration of the head at the same frequency.

E. An example that indicates these theories may be correct

The pressure in the endolymph is a scalar; its "direction" is everywhere normal to the surface. Therefore in contrast to true inertial forces that are vectors, the acoustic pressure will always excite the same hair cells independent of the orientation of the head. So one who experiences this effect should always feel the same motions. And this is exactly what both Steve Ambrose and Rob Rand, who are both acousticians, each experienced. Rob Rand, one of the acoustical researchers on this project, the one who is sensitive to wind turbine acoustic emissions, said of his work in Falmouth, MA in April 2011: "I went outside hoping to feel better. I looked straight at a tree with my eyes, and my brain said the tree was about 20 to 30 degrees elevated and about 20 to 30 degrees to the right. Then I tried to focus on a bush looking straight at it, and again my brain said the bush was off to the right and elevated at about the same angle as before; and the same for the house. For everything I looked at, immediately my brain would say it was elevated and off to the right." Steve Ambrose had exactly the same experience, only not the same angles.

V. CONCLUSIONS

The wind turbine clearly emits acoustic energy at the blade passage frequency, which for the Nordex N100 is

0.7 Hz and about the first six harmonics of 0.7 Hz. This very low infrasound was only found at R2, but that was the only day in which significant power was being generated (about 58%).

Most residents do not hear the wind-turbine sound; noise annoyance is not an issue. The issue is physiological responses that result from the very low frequency infrasound and that appears to trigger motion sickness mainly in some of those who are susceptible to it. These results suggest a relation between wind turbines and motion sickness symptoms in what appears to be a small fraction of those exposed. This finding does not prove our hypothesis that the otoliths are responding to the wind turbine infrasonic emissions. Rather, we can say that the pathway for inducing this condition appears to be the same as airborne transmission through the middle ear and thence to the vestibular sensory cells, but confirmatory research of the pathway is recommended.

Finally, it is shown that the force generated on the otoliths by the pressure from the infrasonic emissions of the wind turbines is perhaps three times larger than the force that would be generated by an acceleration that was in accordance with the U.S. Navy's nauseogenic criteria (Fig. 5 herein). That is, a 0.7 Hz "tone" at 54 dB produces about the same to three times the force as does a 5 m/s^2 acceleration.

VI. ADDITIONAL RESEARCH AND DATA COLLECTION RECOMMENDATIONS

Research to date has not tended to study the effects on humans reported anecdotally in what is probably a minority of wind farms even though these reports are exactly what is to be expected in accordance with ISO 1996-1 (2003). This paper provides part of the foundation upon which such research could be accomplished. Some of the necessary research is listed below. The first item in the list, perform sensing, is discussed in more detail in the Appendix.

(a) Perform the "sensing" tests outlined in the Appendix of this paper.
(b) Demonstrate electric signals going to the brain that emanate from the otoliths; signals that are in sync with the wind turbine emissions, where depending on method this testing would be done with surrogate species.
(c) Develop an understanding of why this phenomenon seems to affect residents near only a small minority of wind farms.
(d) Establish who is and who is not affected by wind turbine infrasonic emissions in various ways.
(e) Establish why this all occurs.

Currently the wind turbine industry presents only A-weighted octave-band[7] data down to 31 Hz, or, frequently 63 Hz, as a minimum. They have stated that the wind turbines do not produce low frequency sound energies. The measurements at Shirley have shown that low frequency infrasound is clearly present and relevant. As indicated by ISO 1996-1 (2003), A-weighting is inadequate and inappropriate for description of infrasound.

ACKNOWLEDGMENTS

The authors wish to acknowledge the extraordinary effort and trust that went into making the testing at the Shirley wind farm possible. First, there is the extraordinary effort of David and George Hessler and their client, Clean Wisconsin, who made these tests happen at the Shirley wind farm. Coupled with this effort were the extraordinary efforts by Glen Reynolds and Forest Voice who also made this test happen. Additionally, our acknowledgment goes to George Hessler for repeated reviews of the paper with helpful inputs and questions, and much credit is due to Bruce Walker for his development of a custom multi-channel time-domain very low frequency, 0.1 Hz, measurement system necessary for advanced signal processing and analysis between and among channels and his custom reprinting of the coherence and spectral plots herein from Shirley. Additionally, credit goes to Robert Rand for repeatedly being a firsthand source of knowledge about the effects of wind turbine emissions and for general thoughts and ideas. Our acknowledgment goes to Dr. Sarah Laurie (Southern Australia), Dr. Robert McMurtry (Ontario, Canada), and Dr. Jay Tibbitts (central Wisconsin); three physicians from around the world who searched their records to provide information on symptoms and histories. And finally, acknowledgments, Alec Salt for providing key references about the otoliths that led us in the right direction; Sumuk Sundarum, MD Ph.D. internal medicine, for review of an early draft; Stephen Chadwick, MD otolaryngology, for initial ideas and review of an early draft; Paul Schomer's good friend Michael Rosnick, MD family medicine, for correcting a misconception about the Eustachian Tube; and to Paul Schomer's daughter Beth Miller, Ph.D., for initial lessons and information on the anatomy and physiology of the ear.

APPENDIX: A TEST FOR PERCEPTION OF THE ACOUSTIC EMISSIONS FROM WIND TURBINES

In Shirley, residents stated that some of them could sense the turning on and off of the wind turbines without any visual or audible clue. This assertion is readily tested; however, it requires the cooperation of the energy company.

Consider the two houses at Shirley where there is no audible sound; the R-1 house and the R-3 house. The residents of the houses, and others who would be subjects, would arrive at the house with the wind turbines off. The test itself would take something like 2 h to perform. Sometime during the first hour, the wind turbines(s) that had been designated by the residents as the turbines they could sense, might or might not be turned on. It would be the residents' task to sense this "turn on" within some reasonable time designated by the residents–say 10 or 30 min. Correct responses (hits) would be sensing a "turn on" when the turbines were turned on, or sensing no change if they were not turned on. Incorrect responses (misses) would be failure to sense a turn on when the turbines were turned on, or (false alarms) would be "sensing" a turn on when the turbines were not turned on.

Similar tests could not necessarily be done starting with the turbines initially on because the subjects, when sensitized find it more difficult to sense a turn off.

[1] The family in the closest dwelling, R-2, reported that the wife and their then 2-yr-old son had the problems; the husband did not have problems. This totally stopped upon their leaving the vicinity of the wind turbines.

[2] Traditionally, participating households are those that receive a share of the proceeds in exchange for having wind turbines or ancillary facilities or equipment on their property. As a part of these agreements, these households are required to agree to not complain about the wind turbines. At Shirley, the energy company also had their "good" neighbor policy wherein all residents who were not eligible to be participating were offered payments for agreeing not to make complaints or take any legal action.

[3] A report, including conclusions and recommendation, was written and signed by these five Shirley technical participants. One of the many interested parties and /or legal entities did not like the conclusions and expunged these from the report without obtaining the approval of the authors while retaining the signature block as it was. Both versions were eventually placed in the record and the complete version as written and signed can be found at the following link: http://psc.wi.gov/apps40/dockets/conten/detail.aspx?dockt_id=2535-CE-100c, go to *"Documents"*; then to "January 2, 2013, 8:40 A.M." (Ex. -Forest Voice-Rand2) (Last viewed 9/29/2014).

[4] Møller and Pedersen present data from 41 wind turbines. In Fig. 1, they plot the turbine sound versus power. These 41 data points form two clumps based on power; one at about 700 kW and the second at about 2 MW. Regression lines fit to two measures of the power both show that the sound level is increasing at a rate of about 12 dB for a tenfold increase in power or about 3.6 dB per decade. Normalized spectra for these same two groups exhibit about a one-third of an octave decrease in the spectrum for the higher power relative to the lower power (Sec. D, Fig. 16). There is also a third much smaller clump of 4 turbines with power ratings of about 100 kW that are not used for much in the paper.

[5] A major effort was made to logically group the "symptoms" in Table I. It is possible that this grouping should have gone further and grouped "sleepiness, drowsiness, and sleep disturbance" with "fatigue and tiredness." That combined "symptom" would have resulted in 100% for the two categories that make up the table.

[6] Montavit (2014) states that 5%–10% of the population are "extremely sensitive" and that 5%–15% are "relatively insensitive." So 5%–10% of the population is probably closer to the percentage that we should be using rather than 15%.

[7] One of the reviewers questioned the use of A-weighted octave band levels. The authors also question this, but the IEC standard requires that the data be reported this way and the wind farm industry concurs.

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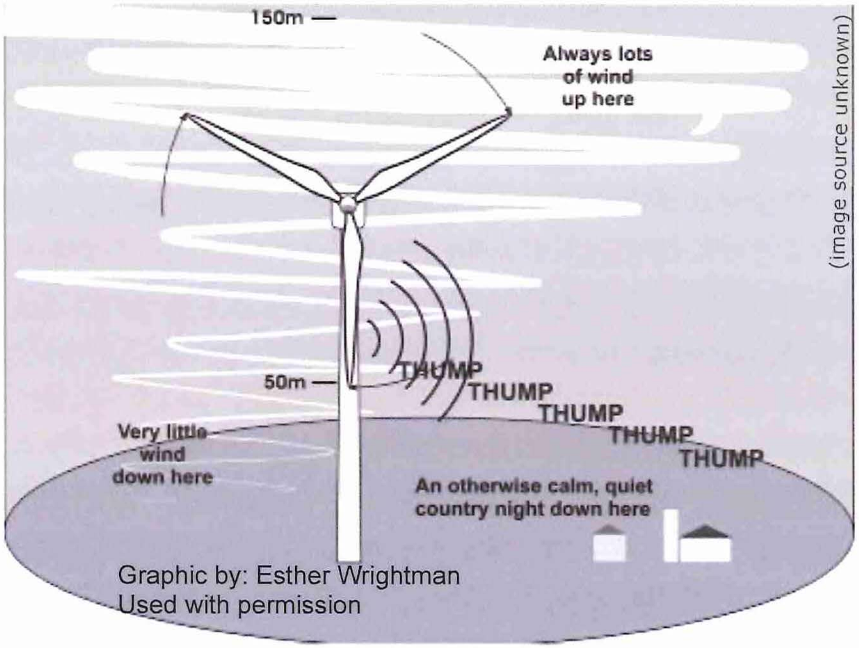
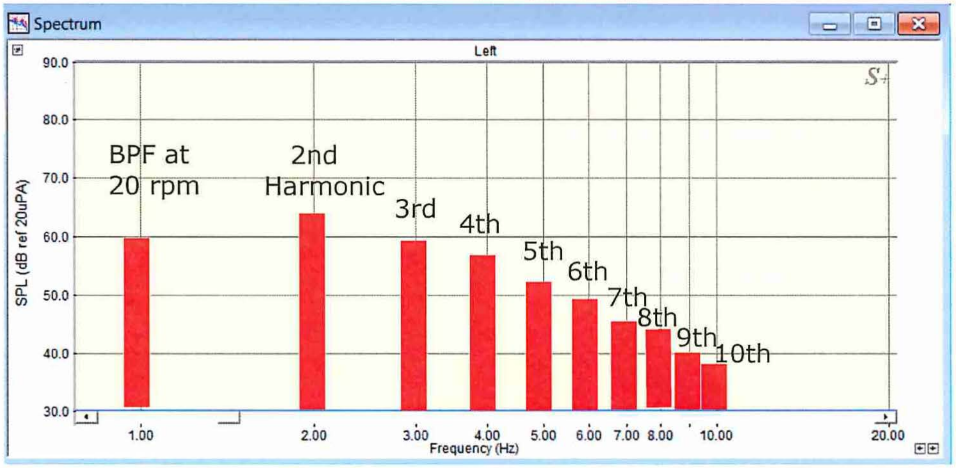
James Direct Testimony, Exhibit 5



Graphic by: Esther Wrightman
Used with permission

(image source unknown)

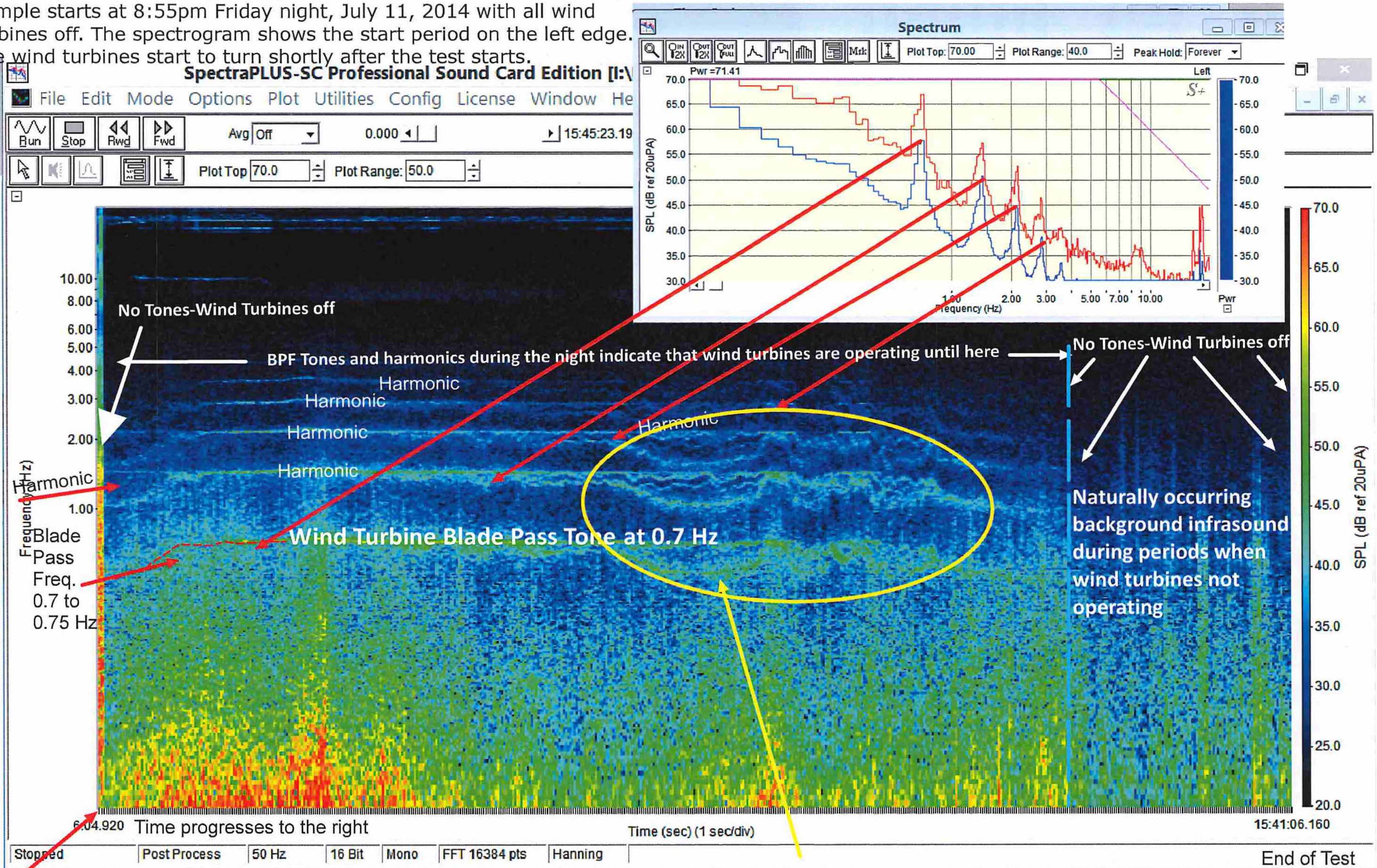


As the blade passes the tower, the low frequency noise and infrasound is generated at a frequency related to the hub's rotation and number of blades. These pressure pulsations appear as tones during analysis but are not heard as tones by most people. Instead they may feel the pressure changes as pulsations, internal organ vibrations, or as a pain (like ear aches or migraines).
This frequency is called the Blade Pass Frequency often abbreviated as BPF.
For modern utility scale wind turbines this frequency is at 1 Hz or lower. A three bladed wind turbine with a hub rotation of 20 revolutions per minute (rpm) has a BPF of 1Hz. This means there is a pressure pulsation emitted into the community once every second. At 15 rpm the BPF is 0.75 Hz and at 10 rpm, 0.5 Hz.

When wind turbine blades rotate past the tower a a short pressure pulse (top graphic) occurs producing a burst of infrasound.
When analyzed the result is a well defined array of tonal harmonics below 10 Hz.
(red bars in figure above)
For impulsive sound of this type the harmonics are all "phase-correlated." This means the peaks of each occur at the same time. Thus, the peaks add together in a linear fashion with their individual maximum sound pressures all coinciding.
Thus, for an impulse having 4 equal amplitude harmonics (BPF, 2nd, 3rd and 4th) each of the same amplitude, the peak level is +12 dB.
10 equal harmonics would produce a peak level of +20 dB.

James Direct Testimony, Exhibit 6

Baseline micro-barometer test results for side-by-side validation testing overnight in the dining/kitchen area of Home 3 (R1 from Shirley Wind Study)
This test period was sampled in parallel using the GRAS 40AZ microphones with the Apollo/Samurai Sound Analysis System
Sample starts at 8:55pm Friday night, July 11, 2014 with all wind turbines off. The spectrogram shows the start period on the left edge. The wind turbines start to turn shortly after the test starts.



No Tones-Wind Turbines off

BPF Tones and harmonics during the night indicate that wind turbines are operating until here

Wind Turbine Blade Pass Tone at 0.7 Hz

Blade Pass Freq. 0.7 to 0.75 Hz

Naturally occurring background infrasound during periods when wind turbines not operating

Time progresses to the right

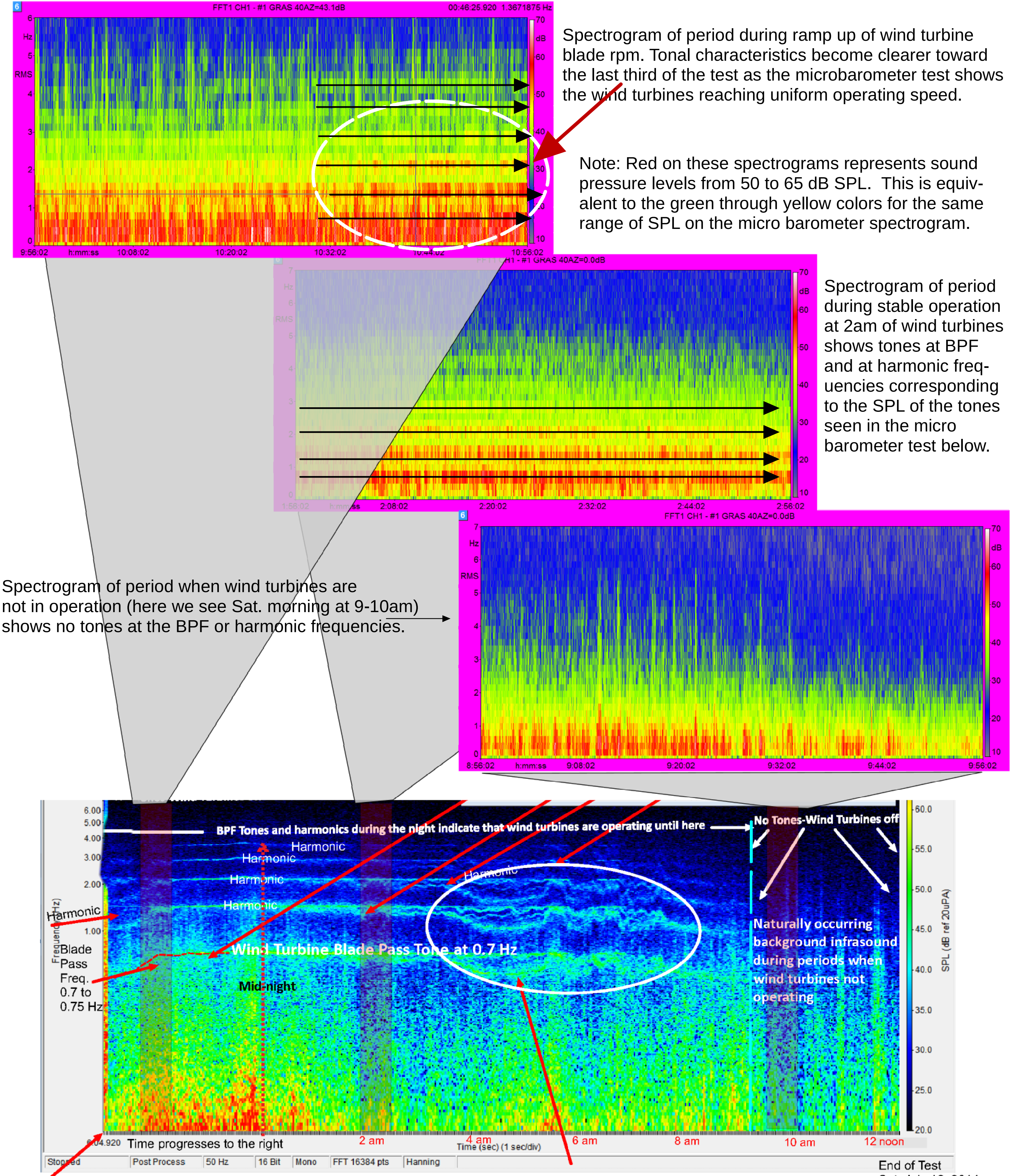
Start of test in R2 Main Floor dining area
Fri. July 11, 2014 at 8:55 pm
Wind turbines were off, but turned on shortly after test started.

The tones from some of the wind turbines deviate from the 0.7 Hz Blade pass frequency indicating that winds or operational changes have altered the rotation speed of some turbines.

End of Test
Sat. July 12, 2014
at 12:25pm CDT
Turbines were off

Next two pages present results of side-by-side tests conducted to validate micro barometer reading with acoustic microphone measurements using GRAS 40AZ microphone and Apollo/Samurai hardware/software.

Results of Side-By-Side Validation Tests showing (on top) one (1) hour spectrograms from GRAS/Apollo/Samurai microphone tests and on the bottom the microbarometer test for Home #3 (R3) spanning the entire test period.



Spectrogram of period during ramp up of wind turbine blade rpm. Tonal characteristics become clearer toward the last third of the test as the microbarometer test shows the wind turbines reaching uniform operating speed.

Note: Red on these spectrograms represents sound pressure levels from 50 to 65 dB SPL. This is equivalent to the green through yellow colors for the same range of SPL on the micro barometer spectrogram.

Spectrogram of period during stable operation at 2am of wind turbines shows tones at BPF and at harmonic frequencies corresponding to the SPL of the tones seen in the micro barometer test below.

Spectrogram of period when wind turbines are not in operation (here we see Sat. morning at 9-10am) shows no tones at the BPF or harmonic frequencies.

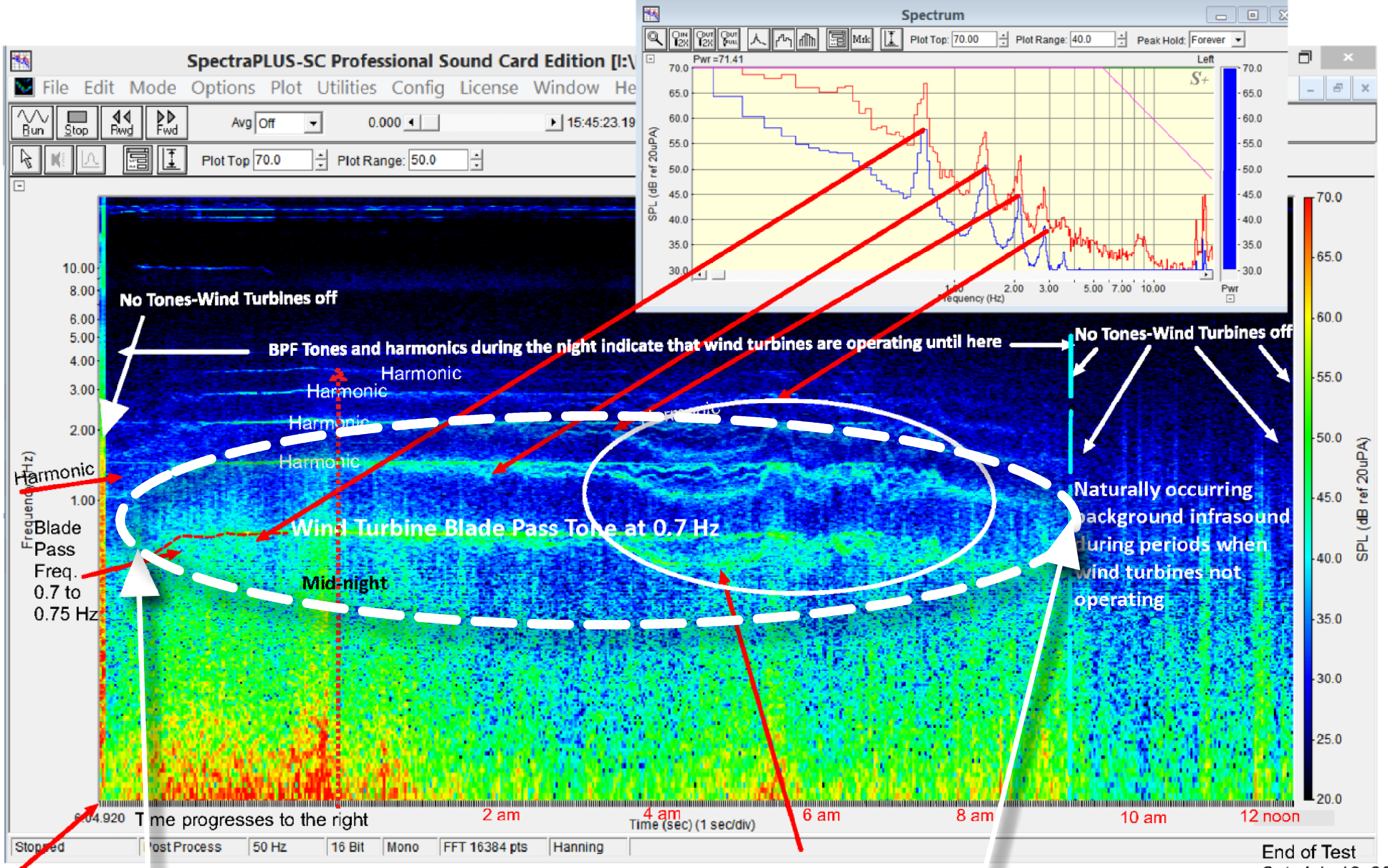
Start of test in R2 Main Floor dining area
Fri. July 11, 2014 at 8:55 pm
Wind turbines were off, but turned on shortly after test started.

The tones from some of the wind turbines deviate from the 0.7 Hz Blade pass frequency indicating that winds or operational changes have altered the rotation speed of some turbines.

End of Test
Sat. July 12, 2014
at 12:25pm CDT
Turbines were off

Comparison of micro-barometer (bottom) tests overnight inside Home 3 (R1) to microphone spectrograms (3 at top) also inside Home #3 (R1)

Home #3 Baseline micro-barometer spectrogram spanning period from 8:55pm Friday night to 12:25pm Sat. afternoon.

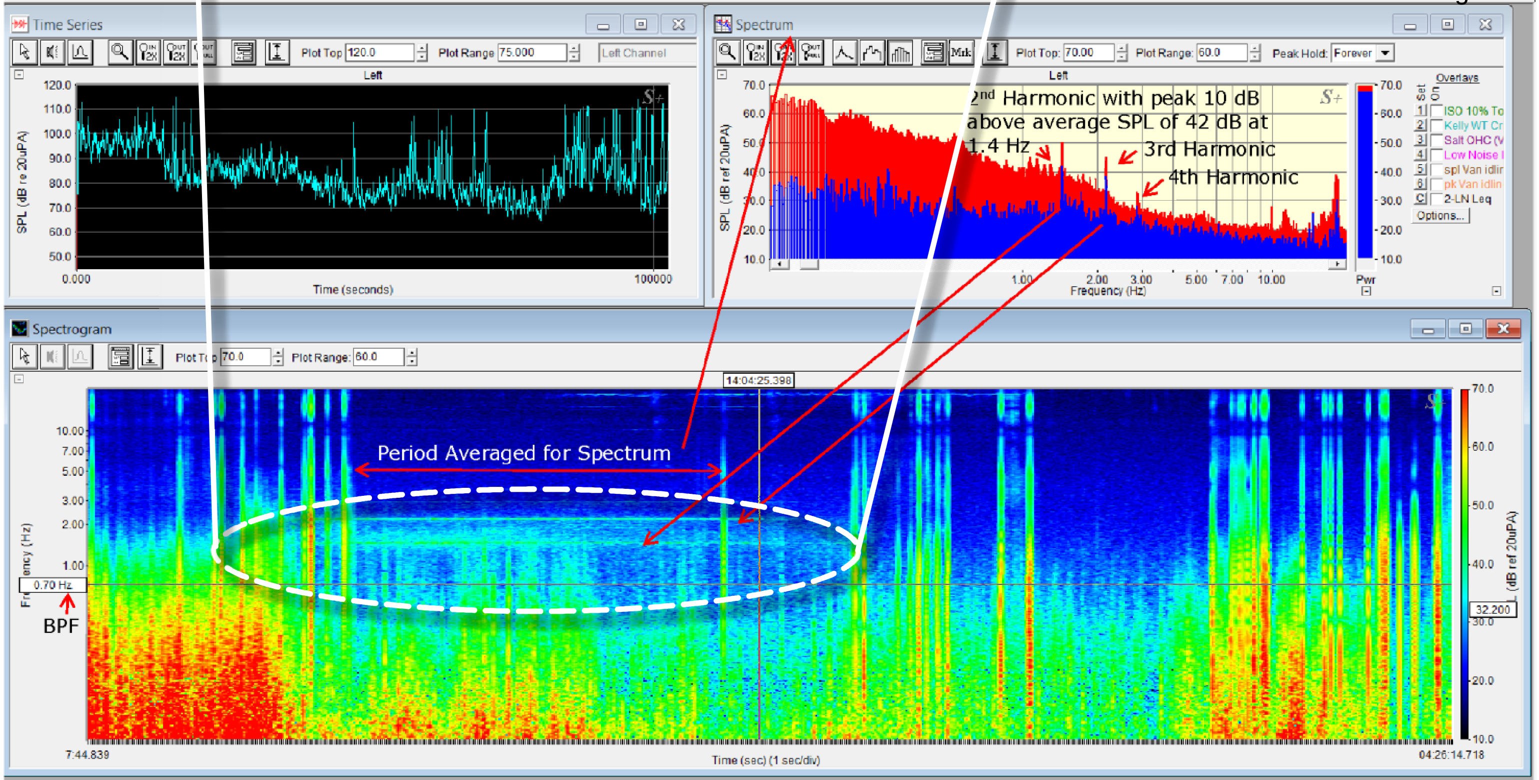


Start of test in R2 Main Floor dining area
Fri. July 11, 2014 at 8:55 pm
Wind turbines were off, but turned on
shortly after test started.

The tones from some of the wind turbines deviate from the 0.7 Hz Blade pass frequency indicating that winds or operational changes have altered the rotation speed of some turbines.

End of Test
Sat. July 12, 2014
at 12:25pm CDT
Turbines were off

Home #9 (22,000 ft. from nearest wind turbine) Baseline micro-barometer spectrogram. Test starts at 3:22pm on Friday, July 11, 2014 and ends 33 hours later spanning about double the time as the test at Home #3. Thus, scale is different from the one at Home #3 above. When adjusted for time scale the tones found at Home #3, 3300 feet from the nearest wind turbine are also found at Home #9 about 4 miles from the nearest wind turbine. The 2nd and 3rd harmonics are the most significant.



Comparison of micro barometer test at Home 9, 4+ miles from wind turbines. Taken concurrent with side-by-side tests inside Home #3 above..