EXHIBIT 1

Analysis of the Potential for a Heat Island Effect in Large Solar Farms

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***Abstract* — Large-scale solar power plants are being built at a rapid rate, and are setting up to use hundreds of thousands of acres of land surface. The thermal energy flows to the environment related to the operation of such facilities have not, so far, been addressed comprehensively. We are developing rigorous computational fluid dynamics (CFD) simulation capabilities for modeling the air velocity, turbulence, and energy flow fields induced by large solar PV farms to answer questions pertaining to potential impacts of solar farms on local microclimate. Using the CFD codes Ansys CFX and Fluent, we conducted detailed 3-D simulations of a 1 MW section of a solar farm in North America and compared the results with recorded wind and temperature field data from the whole solar farm. Both the field data and the simulations show that the annual average of air temperatures in the center of PV field can reach up to 1.9℃ above the ambient temperature, and that this thermal energy completely dissipates to the environment at heights of 5 to 18 m. The data also show a prompt dissipation of thermal energy with distance from the solar farm, with the air temperatures approaching (within 0.3℃) the ambient at about 300 m away of the perimeter of the solar farm. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur. Work is in progress to approximate the flow fields in the solar farm with 2-D simulations and detail the temperature and wind profiles of the whole utility scale PV plant and the surrounding region. The results from these simulations can be extrapolated to assess potential local impacts from a number of solar farms reflecting various scenarios of large PV penetration into regional and global grids.**

***Index Terms* – PV, climate change, heat island, fluid dynamics**

I. INTRODUCTION

Solar farms in the capacity range of 50MW to 500 MW are being proliferating in North America and other parts of the world and those occupy land in the range from 275 to 4000 acres. The environmental impacts from the installation and operation phases of large solar farms deserve comprehensive research and understanding. Turney and Fthenakis [1] investigated 32 categories of impacts from the life-stages of solar farms and were able to categorize such impacts as either beneficial or neutral, with the exception of the "local climate" effects for which they concluded that research and observation are needed. PV panels convert most of the incident solar radiation into heat and can alter the air-flow and temperature profiles near the panels. Such changes, may subsequently affect the thermal environment of near-by populations of humans and other species. Nemet [2] investigated the effect on global climate due to albedo change from widespread installation of solar panels and found this to be small compared to benefits from the reduction in greenhouse gas emissions. However, Nemet did not consider local micro-climates and his analytical results have not been verified with any field data. Donovan [3] assumed that the albedo of ground-mounted PV panels is similar to that of underlying grassland and, using simple calculations, postulated that the heat island effect from installing PV on grassy land would be negligible. Yutaka [4] investigated the potential for large scale of roof-top PV installations in Tokyo to alter the heat island effect of the city and found this to be negligible if PV systems are installed on black roofs.

In our study we aim in comprehensively addressing the issue by modeling the air and energy flows around a solar farm and comparing those with measured wind and temperature data.

II. FIELD DATA DESCRIPTION AND ANALYSIS

Detailed measurements of temperature, wind speed, wind direction, solar irradiance, relative humidity, and rain fall were recorded at a large solar farm in North America. Fig. 1 shows an aerial photograph of the solar farm and the locations where the field measurements are taken.

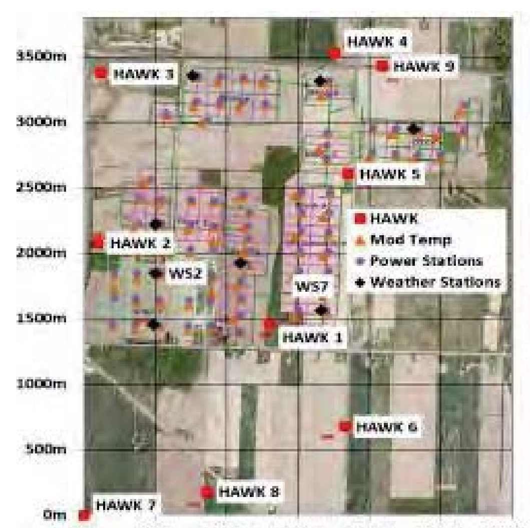


Fig. 1. A picture of the solar farm indicating the locations of the monitoring stations

The field data are obtained from 17 monitoring stations within and around the solar farm, including 8 weather stations (WS) and 9 Hawk stations (HK), all at 2.5 m heights off the ground. There also 80 module temperature (MT) sensors at the back-side of the modules close to each of the corresponding power stations. The WS and MT provide data at 1-min intervals, while the Hawk provides data every 30 minutes. The WS and MT data cover a period of one year from October 2010 to September 2011, while the Hawk data cover a period of 18 months from March 2010 through August 2011.

Hawk stations 3, 6, 7, 8 and 9 are outside the solar farm and were used as reference points indicating ambient conditions. The measurements from Hawk 3, 6, 8 and 9 agree very well confirming that their distances from the perimeter of the solar farm are sufficient for them to be unaffected by the thermal mass of the PV system; Hawk 7 shows higher temperatures likely due to a calibration inaccuracy. In our comparative data analysis we use Hawk 6 as a reference point and, since the prevailing winds are from the south, we selected the section around WS7 as the field for our CFD simulations. Figures 2 to 7 show the difference between the temperatures in Hawk 6 and those in the weather stations WS2 and WS7 within the field, and Hawks 1, 2, 4 and 5 around the solar field.

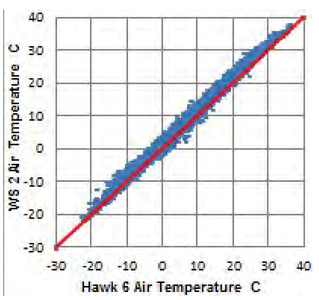


Fig. 2. Air temp WS2 vs. Hawk 6

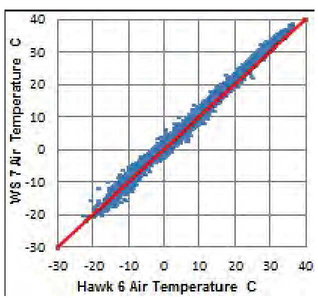


Fig.3. Air temp WS7 vs. Hawk6

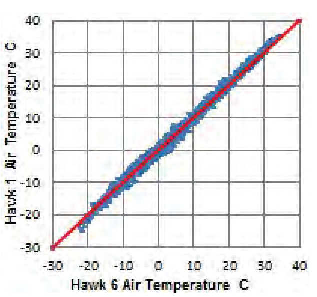


Fig. 4. Air temp Hawk 1 vs. 6

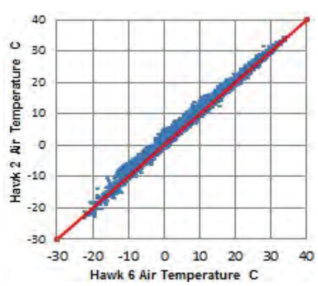


Fig. 5. Air temp Hawk 2 vs. 6

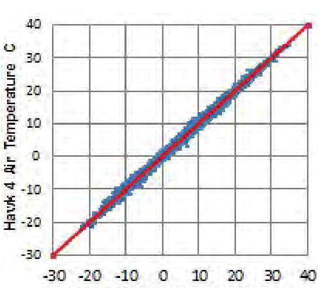


Fig. 6. Air temp Hawk 1 vs. 6

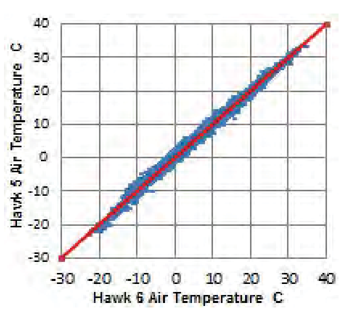


Fig. 7. Air temp Hawk 2 vs. 6

These figures and Table 1 show that with the exception of Hawk 4, the closer the proximity to solar farm the higher the temperature difference from the ambient (indicated by Hawk 6). The relative high temperatures recorded at Hawk 4, and also the relative low temperatures at Hawks 1 and 5 are explained by the prevailing wind direction, which for the time period used in our analysis (8/14/2010-3/14/2011) was Southerly (158°-202°). Hawk 4 is downwind of the solar farm, whereas Hawks 1 and 5 are upwind; the downwind station "feels" more the effect of the heat generated at the solar farm than the ones upwind.

Fig. 8 shows the decline in air temperature as a function of distance to solar farm perimeter. Distances for WS2 and WS7 are negative since they are located inside the solar farm site. WS2 is further into the solar farm and this is reflected in its higher temperature difference than WS7.

TABLE I

DIFFERENCE OF AIR TEMPERATURE (@2.5 M HEIGHTS) BETWEEN THE LISTED WEATHER AND HAWK STATIONS AND THE AMBIENT

Met Station	WS2	WS7	HK1	HK2	HK3	HK4	HK5	HK9
Temp Difference from H6 (^oC)	1.878	1.468	0.488	1.292	0.292	0.609	0.664	0.289
Distance to solar farm perimeter (m)	-440	-100	100	10	450	210	20	300

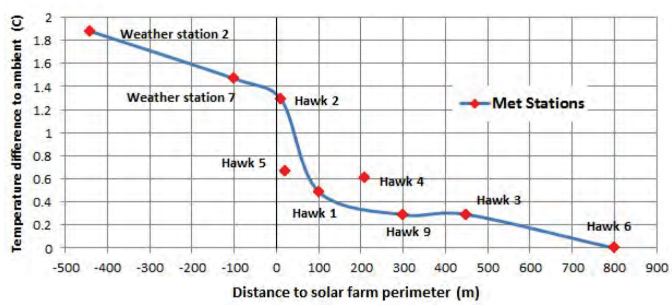


Fig. 8. Air temperature difference as a function of distance from the perimeter of the solar farm. Negative distances indicate locations within the solar farm.

We also examined in detail the temperature differences between the modules and the surrounding air. These vary throughout the year but the module temperatures are consistently higher than those of the surrounding air during the day, whereas at night the modules cool to temperatures below ambient; an example is shown in Fig. 9. Thus, this PV solar farm did not induce a day-after-day increase in ambient temperature, and therefore, adverse micro-climate changes from a potential PV plant are not a concern.

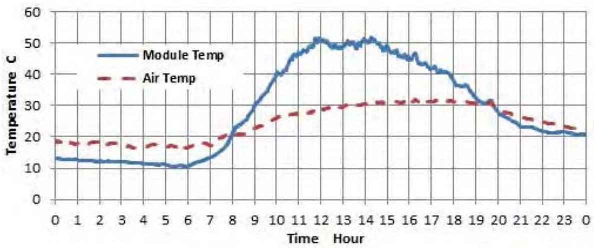


Fig. 9. Comparison of module temperature and air temperature 2.5 m off the ground on a sunny day (July 1, 2011)

III. CFD MODEL DEVELOPMENT

In preliminary simulations we tested the Ansys CFX and FLUENT computational fluid dynamics codes (CFD) and decided to use FLUENT in detailed simulations. FLUENT offers several turbulence schemes including multiple variations of the k-ε models, as well as k-ω models, and Reynolds stress turbulence models. We used the standard, renormalized-group (RNG), and realizable k-ε turbulence closure scheme as it is the most commonly used model in street canyon flow and thermal stratification studies [5]. FLUENT incorporates the P-1 radiation model which affords detailed radiation transfer between the solar arrays, the ground and the ambient air; it also incorporates standard free convection and wind-forced convection models. Our choice of solver was the pressure-based algorithm SIMPLE which uses a relationship between velocity and pressure corrections to enforce mass conservation and obtain the pressure field. We conducted both three-dimensional (3-D) and 2-D simulations.

A 3-D model was built of four fields each covering an area of 93-meters by 73-meters (Fig. 10). Each field contains 23 linear arrays of 73-meter length and 1.8-meter width. Each array has 180 modules of 10.5% rated efficiency, placed facing south at a 25-degree angle from horizontal, with their bottom raised 0.5 m from the ground and their top reaching a height of 1.3 m . Each array was modeled as a single 73 m ×1.8 m × 1 cm rectangular. The arrays are spaced 4 meters apart and the roads between the fields are 8 m. Fig. 10 shows the simulated temperatures on the arrays at 14:00 pm on 7/1/2011, when the irradiance was 966 W/m^2. As shown, the highest average temperatures occur on the last array (array 46). Temperature on the front edge (array 1) is lower than in the center (array 23). Also, temperature on array 24 is lower than array 23, which is apparently caused by the cooling induced by the road space between two fields, and the magnitude of the temperature difference between arrays 24 and 46 is lower than that between arrays 1 and 23, as higher temperature differences from the ambient, result in more efficient cooling.

TABLE II
MODULES TEMPERATURE

Arrays	1	23	24	46
Temperature ℃	46.1	56.4	53.1	57.8

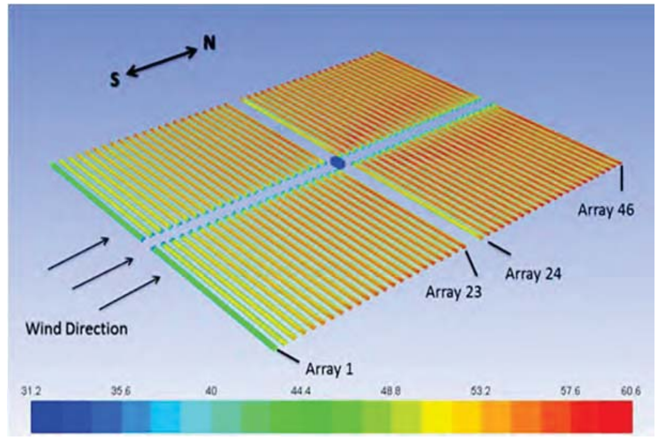


Fig. 10. Module temperatures from 3-D simulations of air flows and thermal exchange during a sunny day

Our simulations also showed that the air temperatures above the arrays at a height of 2.5 m ranged from 28.6 ℃ to 31.1℃; the ambient temperature was 28.6 ℃ (Fig. 11).

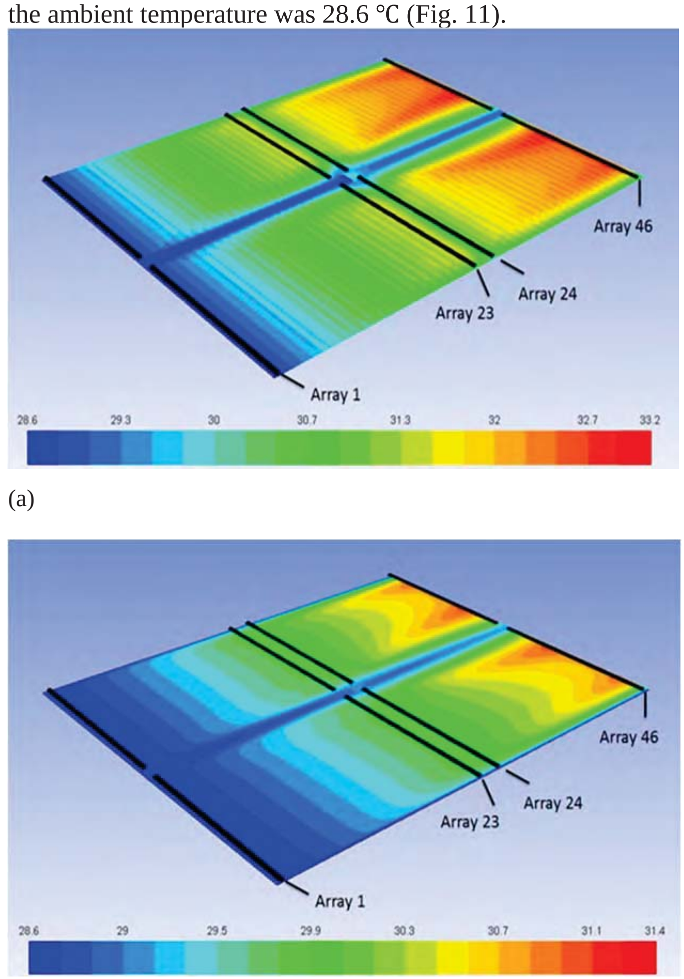


Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

TABLE III
AIR TEMPERATURE

Temperature	Ambient (℃)	Low (℃)	High (℃)	Average (℃)
2.5m height	28.6	28.6	31.1	30.1
1.5m height	28.6	28.6	33.2	30.8

These simulations show a profound cooling effect with increasing height from the ground. It is shown that the temperatures on the back surface of solar panels is up to 30°C warmer than the ambient temperature, but the air above the arrays is only up to 2.5°C higher than the ambient (i.e., 31.1℃). Also the road between the fields allows for cooling, which is more evident at the temperatures 1.5 m off the ground (Fig. 11a). The simulations show that heat build-up at the power station in the middle of the fields has a negligible effect on the temperature flow fields; it was estimated that a power station adds only about 0.4% to the heat generated by the corresponding modules.

The 3-D model showed that the temperature and air velocity fields within each field of the solar farm were symmetrical along the cross-wind axis; therefore a 2-D model of the downwind and the vertical dimensions was deemed to be sufficiently accurate. A 2-D model reduced the computational requirements and allowed for running simulations for several subsequent days using actual 30-min solar irradiance and wind input data. We tested the numerical results for three layers of different mesh sizes and determined that the following mesh sizes retain sufficient detail for an accurate representation of the field data: a) Top layer: 2m by 1m, b) Middle layer: 1.5m by 0.6m, c) Bottom layer: 1m by 0.4m. According to these mesh specifications, a simulation of 92 arrays (length of 388m, height 9m), required a total of 13600 cells. Figures 12-15 show comparisons of the modeled and measured module and air temperatures.

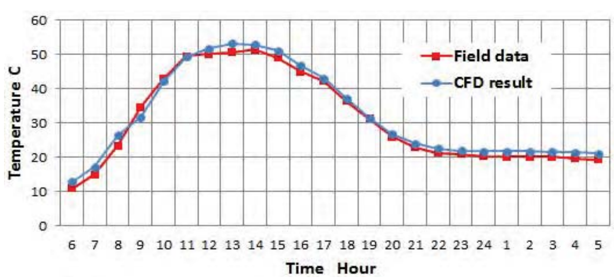


Fig. 12. Comparisons of field and modeled module temperatures; a sunny summer day (7/1/2011); 2-D simulations.

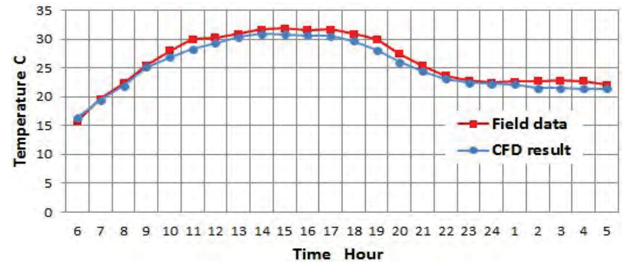


Fig. 13. Comparisons of field and modeled air temperatures at a height of 2.5 m; a sunny summer day (7/1/2011); 2-D simulations.

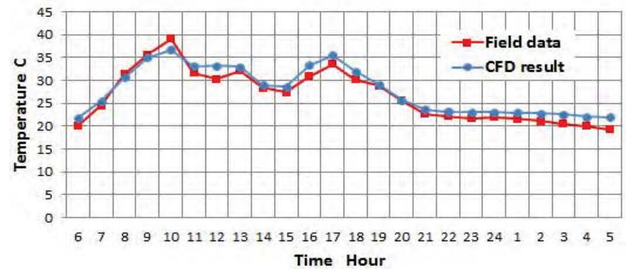


Fig. 14. Comparisons of field and modeled module temperatures; a cloudy summer day (7/11/2011); 2-D simulations.

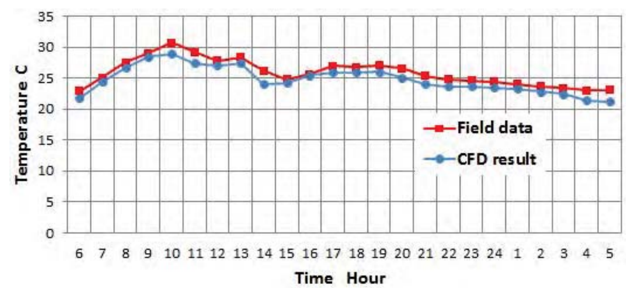
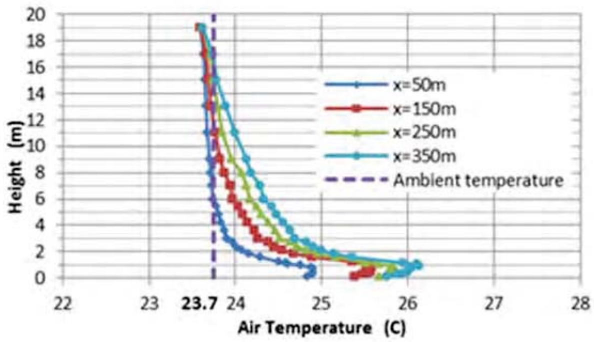
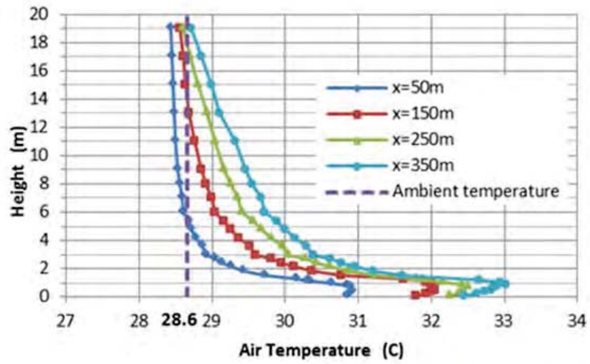


Fig. 15. Comparisons of field and modeled air temperatures at a height of 2.5 m; a cloudy summer day (7/11/2011); 2-D simulations.

Figures 16a and 16b show the air temperature as a function of height at different downwind distances in the morning and afternoon during a sunny summer day. At 9 am (irradiance 500 W/m2, wind speed 1.6 m/s, inlet ambient temperature 23.7℃), the heat from the solar array is dissipated at heights of 5-15m, whereas at 2 pm (irradiance 966 W/m^2, wind speed 2.8m/s, inlet ambient temperature 28.6℃ , the temperature of the panels has reached the daily peak, and the thermal energy takes up to 18 m to dissipate.



(a) 9:00 am



(b) 2:00 pm

Fig. 16 Air temperatures within the solar farm, as a function of height at different downwind distances. From 2-D simulations during a sunny summer day (7/1/2011) at 9 am and 2 pm.

IV. CONCLUSION

The field data and our simulations show that the annual average of air temperatures at 2.5 m of the ground in the center of simulated solar farm section is 1.9℃ higher than the ambient and that it declines to the ambient temperature at 5 to 18 m heights. The field data also show a clear decline of air temperatures as a function of distance from the perimeter of the solar farm, with the temperatures approaching the ambient temperature (within 0.3°C), at about 300 m away. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur.

Our simulations also show that the access roads between solar fields allow for substantial cooling, and therefore, increase of the size of the solar farm may not affect the temperature of the surroundings. Simulations of large (e.g., 1 million m^2) solar fields are needed to test this hypothesis.

ACKNOWLEDGEMENT

We are grateful to First Solar for providing data for this study.

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EXHIBIT 2

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Review Article

Responses of the ear to low frequency sounds, infrasound and wind turbines

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ABSTRACT

Infrasonic sounds are generated internally in the body (by respiration, heartbeat, coughing, etc) and by external sources, such as air conditioning systems, inside vehicles, some industrial processes and, now becoming increasingly prevalent, wind turbines. It is widely assumed that infrasound presented at an amplitude below what is audible has no influence on the ear. In this review, we consider possible ways that low frequency sounds, at levels that may or may not be heard, could influence the function of the ear. The inner ear has elaborate mechanisms to attenuate low frequency sound components before they are transmitted to the brain. The auditory portion of the ear, the cochlea, has two types of sensory cells, inner hair cells (IHC) and outer hair cells (OHC), of which the IHC are coupled to the afferent fibers that transmit "hearing" to the brain. The sensory stereocilia ("hairs") on the IHC are "fluid coupled" to mechanical stimuli, so their responses depend on stimulus velocity and their sensitivity decreases as sound frequency is lowered. In contrast, the OHC are directly coupled to mechanical stimuli, so their input remains greater than for IHC at low frequencies. At very low frequencies the OHC are stimulated by sounds at levels below those that are heard. Although the hair cells in other sensory structures such as the saccule may be tuned to infrasonic frequencies, auditory stimulus coupling to these structures is inefficient so that they are unlikely to be influenced by airborne infrasound. Structures that are involved in endolymph volume regulation are also known to be influenced by infrasound, but their sensitivity is also thought to be low. There are, however, abnormal states in which the ear becomes hypersensitive to infrasound. In most cases, the inner ear's responses to infrasound can be considered normal, but they could be associated with unfamiliar sensations or subtle changes in physiology. This raises the possibility that exposure to the infrasound component of wind turbine noise could influence the physiology of the ear.

1. Introduction

The increasing use of wind turbines as a "green" form of energy generation is an impressive technological achievement. Over time, there have been rapid increases in the size of the towers, blades, and generator capacity of wind turbines, as well as a dramatic increase in their numbers. Associated with the deployment of wind turbines, however, has been a rather unexpected development. Some people are very upset by the noise that some wind turbines produce. Wind turbine noise becomes annoying at substantially lower levels than other forms of transportation noise, with the exception of railroad shunting yards (Pedersen and Waye, 2004; Pedersen and Persson Waye, 2007; Pedersen et al., 2009). Some people with wind turbines located close to their homes have reported a variety of clinical symptoms that in rare cases are severe enough to force them to move away. These symptoms include sleep disturbance, headaches, difficulty concentrating, irritability and fatigue, but also include a number of otologic symptoms including dizziness or vertigo, tinnitus and the sensation of aural pain or pressure (Harry, 2007; Pierpont, 2009). The symptom group has been colloquially termed "wind turbine syndrome" and speculated to result from the low frequency sounds that wind turbines generate (Pierpont, 2009). Similar symptoms resulting from low frequency sound emissions from non-wind turbine sources have also been reported (Feldmann and Pitten, 2004).

On the other hand, engineers associated with the wind industry maintain that infrasound from wind turbines is of no consequence if it is below the audible threshold. The British Wind Energy Association (2010), states that sound from wind turbines are in the 30–50 dBA range, a level they correctly describe as difficult to discern above the rustling of trees [i.e. leaves].

This begs the question of why there is such an enormous discrepancy between subjective reactions to wind turbines and the measured sound levels. Many people live without problems near

Abbreviations: CA, cochlear aqueduct; CM, cochlear microphonic; CSF, cerebrospinal fluid; cVEMP, cervical vestibular evoked myogenic potential; EP, endocochlear potential; IHC, inner hair cell(s); oVEMP, ocular vestibular evoked myogenic potential; OHC, outer hair cell(s); RW, round window; ST, scala tympani; SV, scala vestibuli.

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noisy intersections, airports and factories where sound levels are higher. The answer may lie in the high infrasound component of the sound generated by wind turbines. A detailed review of the effects of low frequency noise on the body was provided by Leventhall (2009). Although it is widely believed that infrasound from wind turbines cannot affect the ear, this view fails to recognize the complex physiology that underlies the ear's response to low frequency sounds. This review considers the factors that influence how different components of the ear respond to low frequency stimulation and specifically whether different sensory cell types of the inner ear could be stimulated by infrasound at the levels typically experienced in the vicinity of wind turbines.

2. The physics of infrasound

Sounds represent fluctuating pressure changes superimposed on the normal ambient pressure, and can be defined by their spectral frequency components. Sounds with frequencies ranging from 20 Hz to 20 kHz represent those typically heard by humans and are designated as falling within the audible range. Sounds with frequencies below the audible range are termed infrasound. The boundary between the two is arbitrary and there is no physical distinction between infrasound and sounds in the audible range other than their frequency. Indeed, infrasound becomes perceptible if presented at high enough level.

The level of a sound is normally defined in terms of the magnitude of the pressure changes it represents, which can be measured and which does not depend on the frequency of the sound. In contrast, for sounds of constant pressure, the displacement of the medium is inversely proportional to frequency, with displacements increasing as frequency is reduced. This phenomenon can be observed as the difference in vibration amplitude between a subwoofer generating a low frequency tone and a tweeter generating a high frequency tone at the same pressure level. The speaker cone of the subwoofer is visibly displaced while the displacement of the tweeter cone is imperceptible. As a result of this phenomenon, vibration amplitudes to infrasound are larger than those to sounds in the auditory range at the same level, with displacements at 1 Hz being 1000 times those at 1 kHz when presented at the same pressure level. This corresponds to an increase in displacement at a rate of 6 dB/octave as frequency is lowered.

3. Overview of the anatomy of the ear

The auditory part of the inner ear, the cochlea, consists of a series of fluid-filled tubes, spiraling around the auditory nerve. A section through the middle of a human cochlea is shown in Fig. 1A. The anatomy of each turn is characterized by three fluid-filled spaces (Fig. 1B): scala tympani (ST) and scala vestibuli (SV) containing perilymph (yellow), separated by the endolymphatic space (ELS)(blue). The two perilymphatic compartments are connected together at the apex of the cochlea through an opening called the helicotrema. Perilymph is similar in ionic composition to most other extracellular fluids (high Na^+, low K^+) while endolymph has a unique composition for an extracellular fluid in the body, being

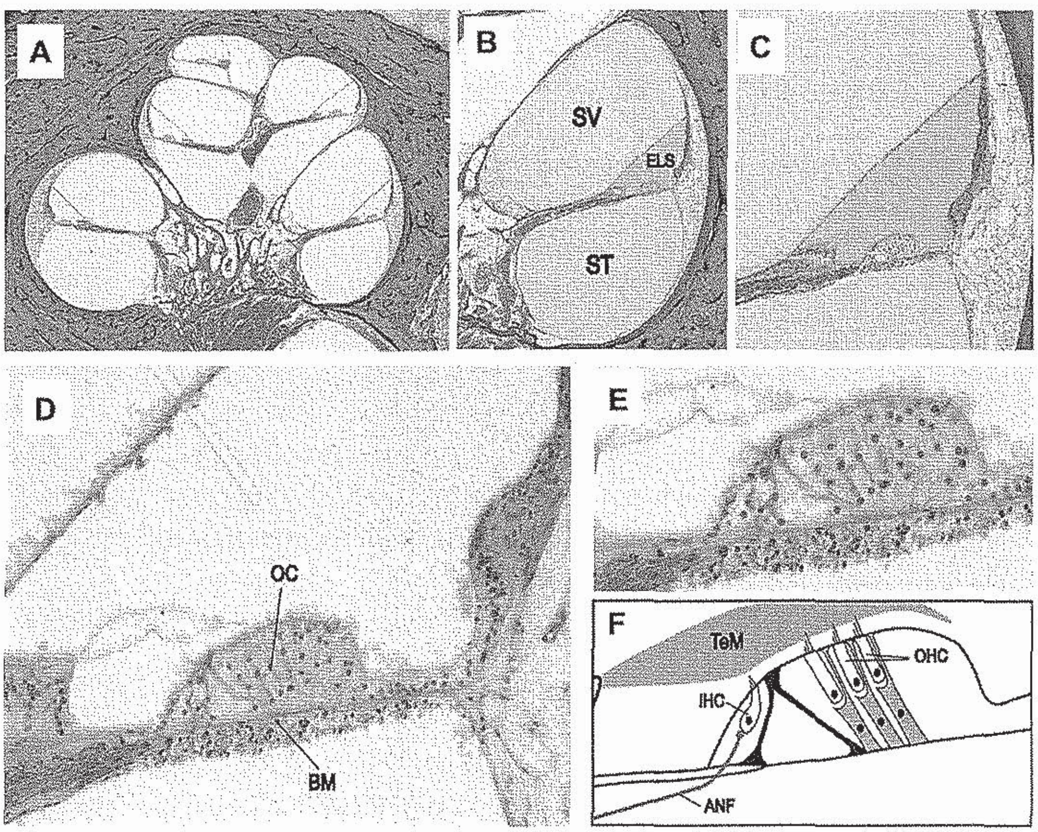

Fig. 1. Panels A–E Cross-section through the human cochlea shown with progressively increasing magnification. Panels B and C The fluid spaces containing perilymph have been colored yellow and endolymph blue. Panel D The sensory structure of the cochlea, the organ of Corti, is colored green. Panel F Schematic showing the anatomy of the main components of the organ of Corti. Abbreviations are: SV: scala vestibuli; ST: scala tympani; ELS: endolymphatic space; OC: organ of Corti; BM: basilar membrane; TeM: tectorial membrane; IHC: inner hair cell; OHC: outer hair cell; ANF: afferent nerve fiber. Original histological images courtesy of Saumil Merchant, MD, Otopathology Laboratory, Massachusetts Eye and Ear Infirmary and Harvard Medical School, Boston.

high in K^+ and low in both Na^+ and Ca^{2+}. It is also electrically polarized by about + 80 mV with respect to perilymph, which is called the endocochlear potential (EP). The main sensory organ of the cochlea (Fig. 1C–E, and shown colored green in Fig. 1D) lies on the basilar membrane between the ELS and the perilymph of ST and is called the organ of Corti. The organ of Corti, seen here in cross section, contains one row of inner hair cells (IHC) and three rows of outer hair cells (OHC) along the spiral length of the cochlea. As shown schematically in Fig. 1F, the sensory hairs (stereocilia) of the OHC have a gradation in length, with the tallest stereocilia embedded in the gelatinous tectorial membrane (TeM) which overlies the organ of Corti in the endolymphatic space (Kimura, 1975). This arrangement allows sound-evoked displacements of the organ of Corti to be converted to a lateral displacement of OHC stereocilia. In contrast, the stereocilia of the IHC do not contact the tectorial membrane, but remain within the fluid of the subtectorial space (Kimura, 1975; Lim, 1986). Because of this difference in how the hair cell stereocilia interact with the TeM, the two types of hair cell respond differently to mechanical stimuli. At low frequencies, the IHC respond according to the velocity of basilar membrane displacement, while OHC respond to the displacement itself (Russell and Sellick, 1983; Dallos, 1984).

The two types of hair cells also contact different types of afferent nerve fibers, sending information to the brain (Spoendlin, 1972; Santi and Tsuprun, 2001). Each IHC is innervated by multiple Type I afferent fibers, with each fiber innervating only a single IHC. The Type I afferents represent the vast majority (95%) of the fibers transmitting information to the brain and as a result it is generally believed that mammals hear with their IHC (Dallos, 2008). In contrast, the OHC contact Type II afferent fibers, which are unmyelinated and make synaptic contacts with a number of OHC. Type II afferents fibers are believed to be unresponsive to sounds and may signal the static position of the organ of Corti (Brown, 1994; Robertson et al., 1999). The OHC also receive substantial efferent innervation (from the brain) while the IHC receive no direct efferent innervation (Spoendlin, 1972).

4. Mechanics of low frequency stimulation

Infrasound entering the ear through the ossicular chain is likely to have a greater effect on the structures of the inner ear than is sound generated internally. The basic principles underlying stimulation of the inner ear by low frequency sounds are illustrated in Fig. 2. Panel A shows the compartments of a simplified, uncoiled cochlea bounded by solid walls with two parallel fluid spaces representing SV and ST respectively that are separated by a distensible membrane representing the basilar membrane and organ of Corti. It is generally agreed that the differential pressure between SV and ST across the basilar membrane is the important factor driving the motion of the basilar membrane (Von Békésy, 1960; Dancer and Franke, 1980; Nakajima et al., 2008; Merchant and Rosowski, 2008). In example A, all the boundaries of the inner ear are solid and noncompliant with the exception of the stapes. In this non-physiologic situation, the stapes applies pressures to SV (indicated by the red arrows) but as the fluid can be considered incompressible, pressures are instantaneously distributed throughout both fluid spaces and pressure gradients across the basilar membrane will be small. In panel B, the round window (RW) and the cochlear aqueduct (CA) have been added to the base of ST. For frequencies below 300 Hz the RW provides compliance between perilymph and the middle ear (Nakajima et al., 2008) and the CA provides fluid communication between perilymph and the cerebrospinal fluid (CSF). Under this condition, pressures applied by the stapes induce small volume flows between the stapes and

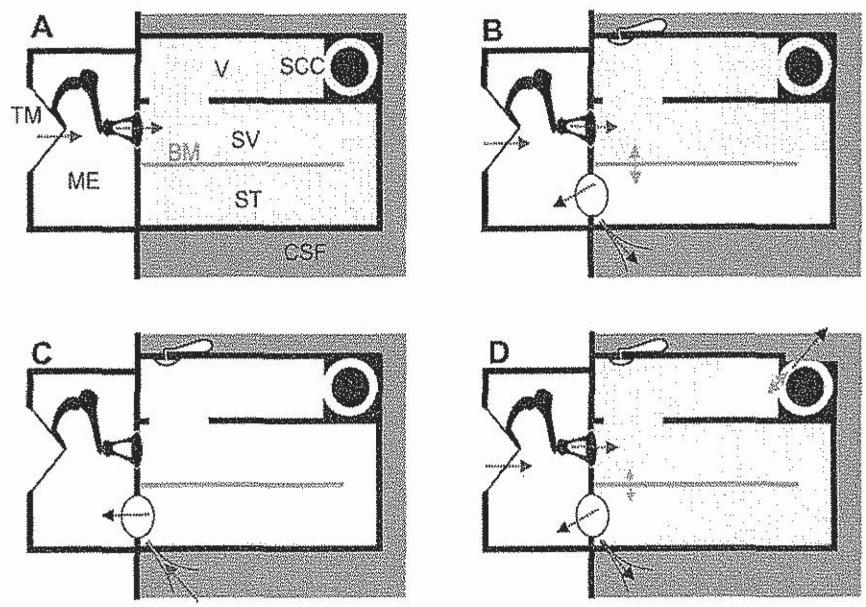

Fig. 2. Schematic representation of the uncoiled inner ear for four different mechanical conditions with low frequency stimulation. Red arrows indicate applied pressure and blue arrows indicate loss to compliant structures. A: indicates a hypothetical condition where the fluid space is rigidly bounded with no "windows" providing compliance. Sound pressure applied by the stapes causes uniform pressures (indicated by color shading) throughout the fluid space, so pressure difference across the basilar membrane and therefore stimulation is minimal. B: The normal situation with compliances provided by the round window and cochlear aqueduct at the base of scala tympani. Pressure differentials cause movement of fluid towards the compliant regions, including a pressure differential across the basilar membrane causing stimulation. C: Situation where low frequency enters scala tympani through the cochlear aqueduct. The main compliant structure is located nearby so pressure gradients across the basilar membrane are small, limiting the amount of stimulation. Infrasound entering through the cochlear aqueduct (such as from respiration and body movements) therefore does not provide the same degree of stimulation as that entering via the stapes. D: Situation with compromised otic capsule, such as superior canal dehiscence. As pressure gradients occur both along the cochlea and through the vestibule and semi-circular canal, the sensory structures in the semi-circular canal will be stimulated. Abbreviations: BM: basilar membrane; CA: cochlear aqueduct; CSF: cerebrospinal fluid; ES: endolymphatic duct and sac; ME: middle ear; RW: round window; SCC: semi-circular canal; ST: scala tympani, SV: scala vestibuli, TM: tympanic membrane; V: vestibule. The endolymphatic duct and sac is not an open pathway but is closed by the tissues of the sac, so it is not considered a significant compliance.

the site(s) of compliance (blue arrows) which requires a pressure gradient to exist along the system, as indicated by the shading. The pressure differential across the basilar membrane will displace it, causing stimulation of the IHC and OHC. This is the situation for external sounds entering the normal cochlea via the ossicular chain. In panel C the situation is compared for sounds originating in the CSF and entering the system through the CA. In this case, the compliant RW is situated close to the location of aqueduct entry, so the major fluid flows and pressure gradients occur locally between these structures. As the stapes and other boundaries in scala vestibuli and the vestibule are relatively noncompliant, pressure gradients across the basilar membrane will be lower than with an equivalent pressure applied by the stapes. For infrasonic frequencies, it was shown that responses to 1 Hz pressure oscillation applied to the fluid in the basal turn of ST were substantially increased when the wall of SV was perforated thereby providing greater compliance in that scala (Salt and DeMott, 1999).

The final condition in Fig. 2D shows the consequences of a "third window" on the SV/vestibule side of the cochlear partition. This causes an increased "air-bone gap" (i.e. an increase in sensitivity to bone conducted vibration and a decreased sensitivity to air conducted sounds, primarily at low frequencies; Merchant and Rosowski, 2008). It may also produce an abnormal sound-induced stimulation of other receptors in the inner ear, such as the hair cells in the ampulla of the semi-circular canal. This is the basis of the Tullio phenomenon, in which externally or internally generated sounds, such as voice, induce dizziness.

Receptors in other organs of the inner ear, specifically both the saccule and the utricle also respond to airborne sounds delivered by the stapes, as discussed in more detail below. The mechanism of hair cell stimulation of these organs is less certain, but is believed to be related to pressure gradients through the sensory epithelium (Sohmer, 2006).

5. Physiologic responses of the ear to low frequency stimuli

5.1. Cochlear hair cells

When airborne sounds enter the ear, to be transduced into an electrical signal by the cochlear hair cells, they are subjected to a number of mechanical and physiologic transformations, some of which vary systematically with frequency. The main processes involved were established in many studies and were summarized by Cheatham and Dallos (2001). A summary of the components is shown in Fig. 3. There are three major processes influencing the sensitivity of the ear to low frequencies. The first arises from the transmission characteristics of sounds through the ossicular structures of the middle ear, which have been shown to attenuate signals at a rate of 6 dB/octave for frequencies below 1000 Hz (Dallos, 1973). As the vibration amplitude in air increases at 6 dB/octave as frequency is lowered, this attenuation characteristic of middle ear transmission results in the displacement of middle ear structures remaining almost constant across frequency for sounds of constant pressure level. A second process attenuating low frequency sounds is the fluid shunting between ST and SV through the helicotrema. The helicotrema has been shown to attenuate frequencies below 100 Hz by 6 dB/octave (Dallos, 1970). The third filter arises from the demonstrated dependence of the IHC on stimulus velocity, rather than displacement (Dallos, 1984). This results in an attenuation of 6 dB/octave for frequencies below approximately 470 Hz for the IHC, and causes a 90° phase difference between IHC and OHC responses (Dallos, 1984). The combined results of these processes are compared with the measured sensitivity of human hearing (ISO226, 2003) in Fig. 3B. The three processes combine to produce the steep decline of sensitivity (up to

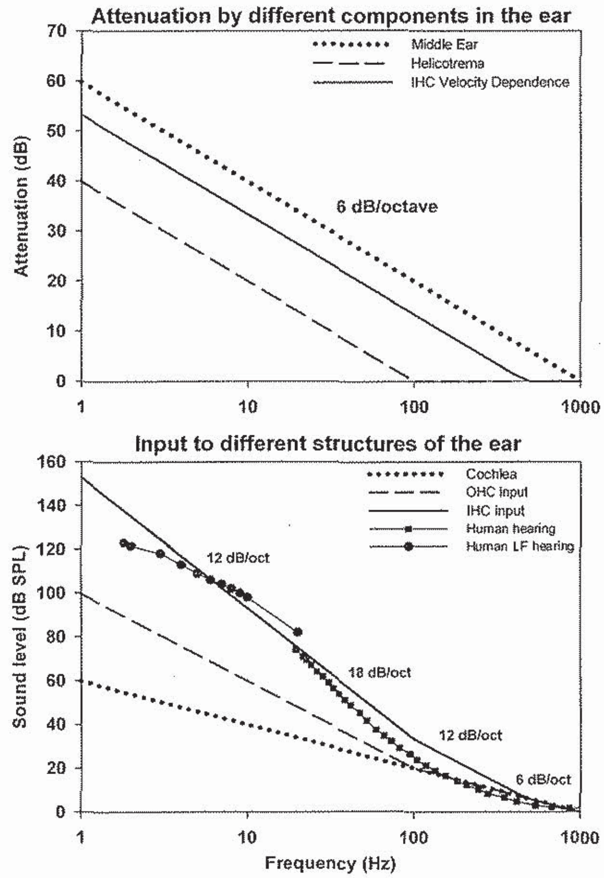

Fig. 3. Upper panel: Estimated properties of high-pass filter functions associated with cochlear signal processing (based on Cheatham and Dallos, 2001). The curves show the low frequency attenuation provided by the middle ear (6 dB/octave below 1000 Hz), by the helicotrema (6 dB/octave below 100 Hz) and by the fluid coupling of the inner hair cells (IHC) resulting in the IHC dependence on stimulus velocity (6 dB/Octave below 470 Hz). Lower panel: Combination of the three processes above into threshold curves demonstrating: input to the cochlea (dotted) as a result of middle ear attenuation; input to the outer hair cells (OHC) as a result of additional filtering by the helicotrema; and input to the IHC as a result of their velocity dependence. Shown for comparison is the sensitivity of human hearing in the audible range (ISO226, 2003) and the sensitivity of humans to infrasounds (Møller and Pederson, 2004). The summed filter functions account for the steep (18 dB/octave) decrease in sensitivity below 100 Hz.

18 dB/octave) in human hearing for frequencies between 100 and 20 Hz. This steep cutoff means that to hear a stimulus at 5 Hz it must be presented at 105 dB higher level than one at 500 Hz. This reflects the fact that the predominant, type I afferent fibers are stimulated by the IHC and that mammals hear with their IHC (Dallos, 2008). However, an important consequence of this underlying mechanism is that the OHC and IHC differ markedly in their responses to low frequency stimuli. As the OHC respond to displacement, rather than velocity, they are not subject to the 6 dB/octave attenuation seen by IHC, so at low frequencies they are stimulated by lower sound levels than the IHC. In theory, the difference between IHC and OHC responses will increase as frequency decreases (becoming over 50 dB at 1 Hz), but in practice, there is interaction between the two types of hair cells which limits the difference as discussed below.

The measured response phase of OHC, IHC and auditory nerve fibers is consistent with the above processes. The cochlear microphonics (CM) recorded in the organ of Corti with low frequency stimuli are in phase with the intracellular potentials of the OHC. This supports the view that the low frequency CM is dominated by

OHC-generated potentials, which follow the displacement of the basilar membrane (Dallos et al., 1972). In contrast, intracellular responses from the IHC lead the organ of Corti CM response by an amount which approaches 90° as frequency is reduced to 100 Hz (Dallos, 1984) corresponding to maximal basilar membrane velocity towards SV (Nuttall et al., 1981). As frequency is lowered, the intracellular potentials of IHC and afferent fiber responses show phase changes consistent with the IHC no longer responding to the increasingly attenuated velocity stimulus, but instead responding to the extracellular potentials generated by the OHC (Sellick et al., 1982; Cheatham and Dallos, 1997). A similar change of phase as frequency is lowered was reported in human psychophysical measurements (Zwicker, 1977) with masking patterns differing by approximately 90° for frequencies above and below 40 Hz. This transition from a response originating from mechanical stimulation of the IHC, to one originating from electrical stimulation of the IHC by large extracellular responses from the OHC may account for the transition of low frequency sensitivity in humans from 18 dB/octave above 20 Hz to 12 dB/octave below 10 Hz (Møller and Pederson, 2004) (Fig. 3B). Near 10 Hz the IHC transition to become primarily stimulated by the more sensitive OHC responses. It can be inferred that if extracellular voltages generated by the OHC are large enough to electrically stimulate the IHC at a specific frequency and level, then the lowest level that the OHC respond to at that frequency must be substantially lower. Based on this understanding of how the sensitivity of the ear arises, one conclusion is that at low frequencies the OHC are responding to infrasound at levels well below those that are heard. On the basis of the calculated input to OHC in Fig. 3B, it is possible that for frequencies around 5 Hz, the OHC could be stimulated at levels up to 40 dB *below* those that stimulate the IHC. Although the OHC at 1 kHz are approximately 12 dB less sensitive than IHC (Dallos, 1984), this difference declines as frequency is lowered and differences in hair cell sensitivity at very low frequencies (below 200 Hz) have not been measured.

Much of the work understanding how the ear responds to low frequency sounds is based on measurements performed in animals. Although low frequency hearing sensitivity depends on many factors including the mechanical properties of the middle ear, low frequency hearing sensitivity has been shown to be correlated with cochlear length for many species with non-specialized cochleas, including humans and guinea pigs (West, 1985; Echteler et al., 1994). The thresholds of guinea pig hearing have been measured with stimulus frequencies as low as 50 Hz, as shown in Fig. 4A. The average sensitivity at 125 Hz for five groups in four studies (Heffner et al., 1971; Miller and Murray, 1966; Walloch and Taylor-Spikes, 1976; Prosen et al., 1978; Fay, 1988) was 37.9 dB SPL, which is 17.6 dB less sensitive than the human at the same frequency and is consistent with the shorter cochlea of guinea pigs. In the absence of data to the contrary, it is therefore reasonable to assume that if low frequency responses are present in the guinea pig at a specific level, then they will be present in the human at a similar or lower stimulus level.

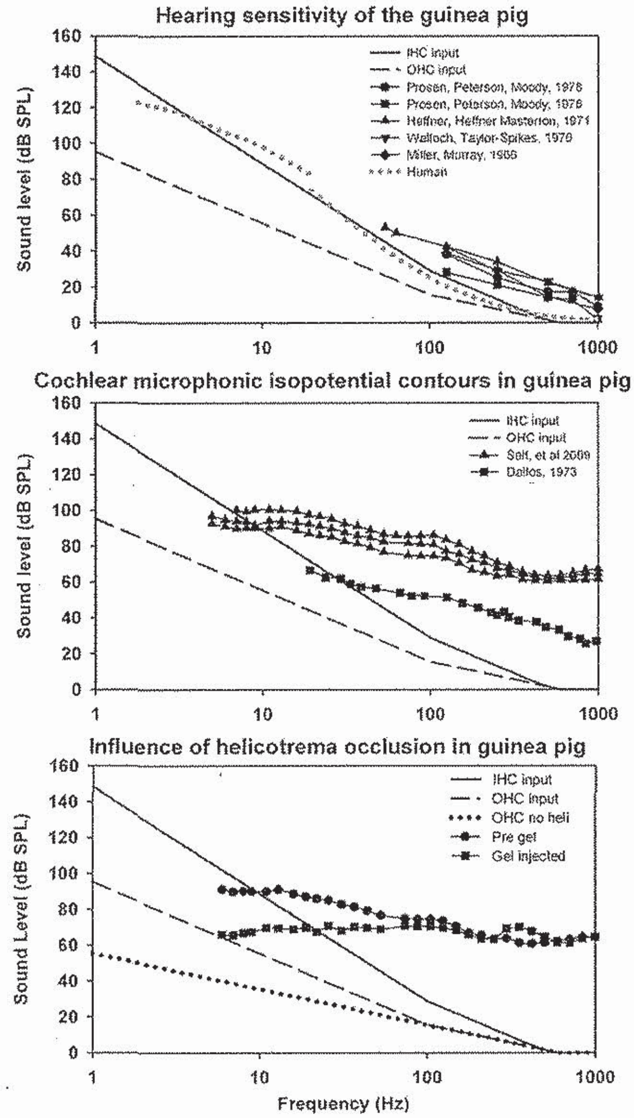

Fig. 4. Upper panel: Similar filter functions as Fig. 3, with parameters appropriate for the guinea pig, and compared with measures of guinea pig hearing. At 125 Hz the guinea pig is approximately 18 dB less sensitive than the human (shown dotted for comparison). Middle panel: Cochlear microphonic isopotential contours in the guinea pig show no steep cutoff below 100 Hz, consistent with input to the OHC being maintained at lower levels than the IHC for low frequencies. Lower panel: Influence of helicotrema occlusion in the guinea pig, produced by injecting 2 μL of hyaluronate gel into the cochlear apex, on the CM isopotential function. Also shown for comparison is the estimated input sensitivity for the OHC with the attenuation by the helicotrema excluded. CM sensitivity curves both have lower slopes than their predicted functions, but the change caused by helicotrema occlusion is comparable.

5.2. *Cochlear microphonic measurements*

Cochlear microphonics (CM) to low frequency tones originate primarily from the OHC (Dallos et al., 1972; Dallos and Cheatham, 1976). The sensitivity of CM as frequency is varied is typically shown by CM isopotential contours, made by tracking a specified CM amplitude as frequency is varied. Fig. 4B shows low frequency CM sensitivity with two different criteria (Dallos, 1973: 3 μV; Salt et al., 2009: 500 μV). The decrease in CM sensitivity as frequency is lowered notably follows a far lower slope than that of human hearing over the comparable frequency range. In the data from Salt et al. (2009), the stimulus level differences between 5 Hz and 500 Hz average only 34 dB (5.2 dB/octave), compared to the 105 dB difference (15.8 dB/octave) for human hearing over the same range. Although these are suprathreshold, extracellular responses, based on an arbitrary amplitude criterion, these findings are consistent with the OHC having a lower rate of cutoff with frequency than the IHC, and therefore responding to lower level stimuli at very low frequencies.

The measured change in CM sensitivity with frequency may include other components, such as a contribution from transducer adaptation at the level of the OHC stereocilia (Kros, 1996). Kennedy et al. (2003) have suggested that adaptation of the mechano-electrical transducer channels is common to all hair cells and contributes to driving active motion of the hair cell bundle. Based on their measurements in cells isolated from the apical turns of neonatal rats, they estimated that the adaptation caused high-pass filtering with a low frequency cutoff frequency of 2/3 of the best frequency for the cochlear location. This type of adaptation, however, does not appear to provide additional attenuation at very low frequencies, as inferred from CM sensitivity curves measured down to 5 Hz. On the contrary, the CM sensitivity curve appears to flatten below 10 Hz, a phenomenon which is currently under investigation in our laboratory.

Fig. 4C shows the influence of plugging the helicotrema with gel on CM sensitivity with frequency, recorded from the basal turn of a guinea pig with a 500 μV criterion (Salt et al., 2009). These relative sensitivity changes, combined with a 90° phase shift in responses, replicate those of Franke and Dancer (1982) and demonstrate the contribution to attenuation provided by the helicotrema for frequencies below approximately 100 Hz. This contrasts with a prior suggestion that the helicotrema of the guinea pig was less effective than that of other species (Dallos, 1970). While the above CM measurements were made with the bulla open, measurements made in both the bulla open/closed conditions with closed sound-field stimulation suggest there is no pronounced frequency dependence of the difference between these conditions below 300 Hz although there may be a level difference of 5–15 dB (Dallos, 1973; Wilson and Johnstone, 1975).

5.3. *Low frequency biasing, operating point, and distortion generation*

As a result of the saturating, nonlinear transducer characteristic of cochlear hair cells (Russell and Sellick, 1983; Kros, 1996), the fidelity of cochlear transduction depends highly on the so-called operating point of the cochlear transducer, which can be derived by Boltzmann analysis of the CM waveform (Patuzzi and Moleirinho, 1998; Patuzzi and O'Beirne, 1999). The operating point can be regarded as the resting position of the organ of Corti or its position during zero crossings of an applied stimulus (which may not be identical, as stimulation can itself influence operating point). Small displacements of operating point have a dramatic influence on even-order distortions generated by the cochlea ($2f$, f_2-f_1) while having little influence on odd-order distortions ($3f$, $2f_1-f_2$) until displacements are large (Frank and Kössl, 1996; Sirjani et al., 2004). Low frequency sounds (so-called bias tones) have been shown to modulate distortion generated by the ear by their displacement of the operating point of the organ of Corti (Brown et al., 2009). In normal guinea pigs, 4.8 Hz bias tones at levels of 85 dB SPL have been shown to modulate measures of operating point derived from an analysis of CM waveforms (Brown et al., 2009; Salt et al., 2009). This is a level that is substantially below the expected hearing threshold of the guinea pig at 4.8 Hz. In animals where the helicotremea was occluded by injection of gel into the perilymphatic space at the cochlear apex, even lower bias levels (down to 60 dB SPL) modulate operating point measures (Salt et al., 2009). These findings are again consistent with the OHC being the origin of the signals measured and the OHC being more responsive to low frequency sounds than the IHC. A similar hypersensitivity to 4.8 Hz bias tones was also found in animals with surgically-induced endolymphatic hydrops (Salt et al., 2009). This was thought to be related to the occlusion of the helicotrema by the displaced membranous structures bounding the hydropic endolymphatic space in the apical turn. In some cases of severe hydrops, Reissner's membrane was seen to herniate into ST. As endolymphatic hydrops is present both in patients with Meniere's disease and in a significant number of asymptomatic patients (Merchant et al., 2005), the possibility exists that some individuals may be more sensitive to infrasound due the presence of endolymphatic hydrops.

In the human ear, most studies have focused on the $2f_1-f_2$ distortion product, as even-order distortions are difficult to record in humans. The $2f_1-f_2$ component has been demonstrated to be less sensitive to operating point change (Sirjani et al., 2004; Brown et al., 2009). Using different criteria of bias-induced distortion modulation, the dependence on bias frequency was systematically studied in humans for frequencies down to 25 Hz, 6 Hz and 15 Hz respectively (Bian and Scherrer, 2007; Hensel et al., 2007; Marquardt et al., 2007). In each of these studies, the bias levels required were above those that are heard by humans, but in all of them the change of sensitivity with frequency followed a substantially lower slope than the hearing sensitivity change as shown in Fig. 5. Again this may reflect the OHC origins of acoustic emissions, possibly combined with the processes responsible for the flattening of equal loudness contours for higher level stimuli, since the acoustic emissions methods are using probe stimuli considerably above threshold. Although in some regions, slopes of 9–12 dB/octave were found, all showed slopes of 6 dB/octave around the 20 Hz region where human hearing falls most steeply at 18 dB/octave. It should also be emphasized that each of these studies selected a robust modulation criterion and was not specifically directed at establishing a threshold for the modulation response at each frequency. Indeed, in the data of Bian and Scherrer (2007) (their Fig. 3), significant modulation can be seen at levels down to 80 dB SPL at some of the test frequencies. In one of the studies (Marquardt et al., 2007) equivalent measurements were performed in guinea pigs. Although somewhat lower slopes were observed in guinea pigs it is remarkable that stimulus levels required for modulation of distortion were within 5–10 dB of each other for guinea pigs and humans across most of the frequency range. In this case the guinea pig required lower levels than the human. Although the threshold of sensitivity cannot be established from these studies, it is worth noting that for distortion product measurements in the audible range, "thresholds" typically require stimulus levels in the 35–45 dB SPL range (Lonsbury-Martin et al., 1990). In the Marquardt study, the bias tone level required at 500 Hz is over 60 dB above hearing threshold at that frequency.

5.4. *Feedback mechanisms stabilizing operating point*

The OHC not only transduce mechanical stimuli to electrical responses, but also respond mechanically to electrical stimulation

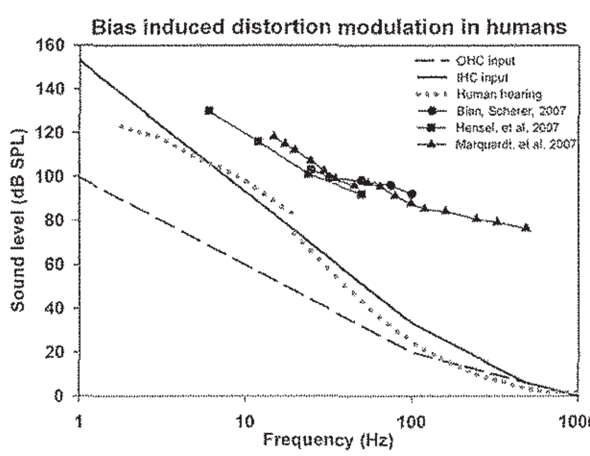

Fig. 5. Frequency dependence of low frequency bias-induced modulation of the $2f_1-f_2$ distortion product measured in the external ear canal of humans in three studies, compared with estimated input functions and human hearing sensitivity. Below 100 Hz the sensitivity to bias falls off at a much lower slope than human hearing, consistent with the response originating from OHC with a lower cutoff slope.

(reviewed by Dallos, 2008) in a manner that provides mechanical amplification. This "active tuning" primarily enhances responses to high stimulus frequencies and is thought to provide little or no active gain with stimuli below approximately 1 kHz (Sellick et al., 2006). For low frequency stimulation, however, basilar membrane modulation by the low frequency tone does have a major influence on the mechanics at the best frequency of high frequency tones i.e. on the active tuning process (Patuzzi et al., 1984). It has been suggested that slow mechanical movements of the OHC may play a part in stabilizing the operating point of the transducer (LePage, 1987, 1989) so the OHC may participate in an active cancellation of low frequency sounds. In models of the cochlear transducer, it was proposed that negative feedback occurred at low frequencies (in which the OHC opposed movements of the basilar membrane), which becomes a positive feedback at the best frequency for the region (Mountain et al., 1983). Chan and Hudspeth (2005) have also suggested OHC motility may be exploited to maintain the operating point of a fast amplifier in the hair cell bundle. However, this possibility has recently been questioned by Dallos (Ashmore et al., 2010) for a number of reasons, one of which is the somatic motor protein, prestin, has an extremely fast response capability. So the interrelationships between hair cell motility and transduction, and between OHC and IHC remain an intense focus of current research. For low frequencies, it has been shown that an out-of phase motion exists between the IHC reticular lamina and the overlying TM so that electromechanical action of the OHC may stimulate the IHC directly, without involvement of the basilar membrane (Nowotny and Gummer, 2006). The possible roles of the OHC and efferent systems are made more complex by recent findings of reciprocal synapses between OHC and their efferent terminals, seen as afferent and efferent synapses on the same fiber (Thiers et al., 2008). One explanation for this system is that the synapses may locally (without involvement of the central nervous system) coordinate the responses of the OHC population so that optimum operating point is maintained for high frequency transduction.

There is some evidence for active regulation of operating point based on the biasing of acoustic emission amplitudes by low frequency tones in which a "hysteresis" was observed (Bian et al., 2004). The hysteresis was thought to result from active motor elements, either in the stereocilia or the lateral wall of the OHC, shifting the transducer function in the direction of the bias. A similar hysteresis was also reported by Lukashkin and Russell (2005) who proposed that a feedback loop was present during the bias that keeps the operating point at its most sensitive region, shifting it in opposite directions during compression and rarefaction phase of the bias tone thereby partially counteracting its effects.

If there are systems in the cochlea to control operating point as an integral component of the amplification process, they would undoubtedly be stimulated in the presence of external infrasound.

5.5. *Vestibular function*

The otolith organs, comprising of the saccule and utricle, respond to linear accelerations of the head (Uzun-Coruhlu et al., 2007) and the semi-circular canals respond to angular acceleration. These receptors contribute to the maintenance of balance and equilibrium. In contrast to the hair cells of the cochlea, the hair cells of the vestibular organs are tuned to very low frequencies, typically below 30 Hz (Grossman et al., 1988). Frequency tuning in vestibular hair cells results from the electrochemical properties of the cell membranes (Manley, 2000; Art and Fettiplace, 1987) and may also involve active mechanical amplification of their stereociliary input (Hudspeth, 2008; Rabbitt et al., 2010). Although vestibular hair cells are maximally sensitive to low frequencies they typically do not respond to airborne infrasound. Rather, they normally respond to mechanical inputs resulting from head movements and positional changes with their output controlling muscle reflexes to maintain posture and eye position. At the level of the hair cell stereocilia, although vibrations originating from head movements and low frequency sound would be indistinguishable, the difference in sensitivity lies in the coupling between the source stimulus and the hair cell bundle. Head movements are efficiently coupled to the hair cell bundle, while acoustic stimuli are inefficiently coupled due to middle ear characteristics and the limited pressure gradients induced within the structure with sound stimuli (Sohmer, 2006).

In a similar manner to cochlear hair cells, which respond passively (i.e. without active amplification) to stimuli outside their best frequency range, vestibular hair cells respond passively to stimuli outside their best frequency range. The otolith organs have been shown to respond to higher, acoustic frequencies delivered in the form of airborne sounds or vibration. This has been demonstrated in afferent nerve fiber recordings from vestibular nerves (Young et al., 1977; McCue and Guinan, 1994; Curthoys et al., 2006) and has recently gained popularity as a clinical test of otolith function in the form of vestibular evoked myogenic potential (VEMP) testing (Todd et al., 2003; Zhou and Cox, 2004; Curthoys, 2010).These responses arise because higher frequency stimuli are more effectively coupled to the otolithic hair cells. But as sound or vibration frequency is reduced, its ability to stimulate the vestibular organs diminishes (Murofushi et al., 1999; Hullar et al., 2005; Todd et al., 2008). So for very low frequencies, even though the hair cell sensitivity is increasing as active tuning is invoked, mechanical input is being attenuated. While there have been many studies of vestibular responses to physiologic stimuli (i.e. head accelerations, rotations, etc) comprising of infrasonic frequency components, we are unaware of any studies that have directly investigated vestibular responses to airborne infrasound of similar frequency composition. As people do not become unsteady and the visual field does not blur when exposed to high-level infrasound, it can be concluded that sensitivity is extremely low.

In some pathologic conditions, coupling of external infrasound may be greater. It is known that "third window" defects, such as superior canal dehiscence increase the sensitivity of labyrinthine receptors to sounds (Wit et al., 1985; Watson et al., 2000; Carey et al., 2004), and are exhibited as the Tullio phenomenon (see earlier section). To our knowledge, the sensitivity of such patients to controlled levels of infrasound has never been evaluated. In this respect, it needs to be considered that vestibular responses to stimulation could occur at levels below those that are perceptible to the patient (Todd et al., 2008).

5.6. *Inner ear fluids changes*

Some aspects of cochlear fluids homeostasis have been shown to be sensitive to low frequency pressure fluctuations in the ear. The endolymphatic sinus is a small structure between the saccule and the endolymphatic duct which has been implicated as playing a pivotal role in endolymph volume regulation (Salt, 2005). The sinus has been shown to act as a valve, limiting the volume of endolymph driven into the endolymphatic sac by pressure differences across the endolymphatic duct (Salt and Rask-Andersen, 2004). The entrance of saccular endolymph into the endolymphatic sac can be detected either by measuring the K^+ concentration in the sac (as saccular endolymph has substantially higher K^+ concentration) or by measuring hydrostatic pressure. The application of a sustained pressure to the vestibule did not cause K^+ elevation or pressure increase in the sac, confirming that under this condition, flow was prevented by the membrane of the sinus acting as a valve. In contrast, the application of 5 cycles at 0.3 Hz to the external ear canal, caused a K^+ increase in the sac, confirming that oscillation of pressure applied to the sinus allowed pulses of endolymph to be driven from the sinus into the endolymphatic sac. The pressure changes driving these pulses was large, comparable to those produced by contractions of the tensor tympani muscle, as occurs during swallowing. Tensor tympani contractions produce displacements of the stapes towards the vestibule for a duration of approximately 0.5 s (~2 Hz), which induce large EP changes and longitudinal movements of endolymph within the cochlea (Salt and DeMott, 1999). The lowest sound level that drives endolymph movements is currently unknown.

A therapeutic device (the Meniett: www.meniett.com; Odkvist et al., 2000) that delivers infrasound to the inner ear is widely used to treat Meniere's disease in humans (a disease characterized by endolymphatic hydrops). The infrasonic stimulus (6 Hz or 9 Hz) is delivered by the device in conjunction with sustained positive pressure in the external canal. An important aspect of this therapy, however, is that a tympanostomy tube is placed in the tympanic membrane before the device is used. The tympanostomy tube provides an open perforation of the tympanic membrane which shunts pressure across the structure, so that ossicular movements (and cochlear stimulation) are minimized, and the pressures are applied directly to the round window membrane. Nevertheless, the therapeutic value of this device is based on infrasound stimulation influencing endolymph volume regulation in the ear.

As presented above, endolymphatic hydrops, by occluding the perilymph communication pathway through the helicotrema, makes the ear more sensitive to infrasound (Salt et al., 2009). It has also been shown that non-damaging low frequency sounds in the acoustic range may themselves cause a transient endolymphatic hydrops (Flock and Flock, 2000; Salt, 2004). The mechanism underlying this volume change has not been established and it has never been tested whether stimuli in the infrasound range cause endolymphatic hydrops.

Although infrasound at high levels apparently does not cause direct mechanical damage to the ear (Westin, 1975; Jauchem and Cook, 2007) in animal studies it has been found to exacerbate functional and hair cell losses resulting from high level exposures of sounds in the audible range (Harding et al., 2007). This was explained as possibly resulting from increased mixture of endolymph and perilymph around noise induced lesion sites in the presence of infrasound.

6. Wind turbine noise

Demonstrating an accurate frequency spectrum of the sound generated by wind turbines creates a number of technical problems. One major factor that makes understanding the effects of wind turbine noise on the ear more difficult is the widespread use of A-weighting to document sound levels. A-weighting shapes the measured spectrum according to the sensitivity of human hearing, corresponding to the IHC responses. As we know the sensitivity for many other elements of inner ear related to the OHC do not decline at the steep slope seen for human hearing, then A-weighting considerably underestimates the likely influence of wind turbine noise on the ear. In this respect, it is notable that in none of the physiological studies in the extensive literature reporting cochlear function at low frequencies were the sound stimuli A-weighted. This is because scientists in these fields realize that shaping sound levels according to what the brain perceives is not relevant to understanding peripheral processes in the ear. A-weighting is also performed for technical reasons, because measuring unweighted spectra of wind turbine noise is technically challenging and suitable instrumentation is not widely available. Most common approaches to document noise levels (conventional sound level meters, video cameras, devices using moving coil microphones, etc) are typically insensitive to the infrasound component. Using appropriate instrumentation, Van den Berg showed that wind turbine noise was dominated by infrasound components, with energy increasing between 1000 Hz and 1 Hz (the lowest frequency that was measured) at a rate of approximately 5.5 dB/octave, reaching levels of approximately 90 dB SPL near 1 Hz Sugimoto et al. (2008) reported a dominant spectral peak at 2 Hz with levels monitored over time reaching up to 100 dB SPL. Jung and Cheung (2008) reported a major peak near 1 Hz at a level of approximately 97 dB SPL. In most studies of wind turbine noise, this high level, low frequency noise is dismissed on the basis that the sound is not perceptible. This fails to take into account the fact that the OHC are stimulated at levels that are not heard.

7. Conclusions

The fact that some inner ear components (such as the OHC) may respond to infrasound at the frequencies and levels generated by wind turbines does not necessarily mean that they will be perceived or disturb function in any way. On the contrary though, if infrasound is affecting cells and structures at levels that cannot be heard this leads to the possibility that wind turbine noise could be influencing function or causing unfamiliar sensations. Long-term stimulation of position-stabilizing or fluid homeostasis systems could result in changes that disturb the individual in some way that remains to be established. We realize that some individuals (such as fighter pilots) can be exposed to far higher levels of infrasound without undue adverse effects. In this review, we have confined our discussion to the possible direct influence of infrasound on the body mediated by receptors or homeostatic processes in the inner ear. This does not exclude the possibility that other receptor systems, elsewhere in the body could contribute to the symptoms of some individuals.

The main points of our analysis can be summarized as follows:

1) Hearing perception, mediated by the inner hair cells of the cochlea, is remarkably insensitive to infrasound.
2) Other sensory cells or structures in the inner ear, such as the outer hair cells, are more sensitive to infrasound than the inner hair cells and can be stimulated by low frequency sounds at levels below those that are heard. The concept that an infrasonic sound that cannot be heard can have no influence on inner ear physiology is incorrect.
3) Under some clinical conditions, such as Meniere's disease, superior canal dehiscence, or even asymptomatic cases of endolymphatic hydrops, individuals may be hypersensitive to infrasound.
4) A-weighting wind turbine sounds underestimates the likely influence of the sound on the ear. A greater effort should be made to document the infrasound component of wind turbine sounds under different conditions.
5) Based on our understanding of how low frequency sound is processed in the ear, and on reports indicating that wind turbine noise causes greater annoyance than other sounds of similar level and affects the quality of life in sensitive individuals, there is an urgent need for more research directly addressing the physiologic consequences of long-term, low level infrasound exposures on humans.

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EXHIBIT 3

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KUMEYAAY AND OCOTILLO WIND TURBINE FACILITIES

NOISE MEASUREMENTS

28 February 2014

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EXECUTIVE SUMMARY

Noise measurements were obtained for wind turbines (WTs) at the Kumeyaay Wind Farm (Kumeyaay Wind) and Ocotillo Wind Energy Facility (Ocotillo Wind or OWEF) between April 28 and April 30, 2013. This report conclusively documents the presence of infrasound and low frequency noise (ILFN) generated by the two facilities' wind turbines at residential and other locations up to 6 miles from the wind turbines.

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[1] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[2] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[3] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[4]

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[1] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[2] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

[3] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[4] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

Furthermore, Matsumoto et al.[5] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

INTRODUCTION

As requested, Wilson, Ihrig & Associates (WIA) performed noise measurements in the vicinity of the Kumeyaay Wind Farm, located on the Campo Indian Reservation near Boulevard, California. We also took similar measurements in the vicinity of the Ocotillo Wind Energy Facility located near Ocotillo, California. The purpose of the measurements was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN[6], and how far the ILFN is propagated. A subsidiary goal was to accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and other environmental impacts of the ILFN generated.

Between April 28 and April 30, 2013, we recorded noise samples at numerous residential and reference locations near each wind turbine facility. The wind turbines at both facilities were operating the entire time during which we took our noise measurements. Although it would have been our preference to also measure ambient noise conditions with all wind turbines taken out of operation, turbine operation was out of our control. In any event, even without measurements of the ambient noise sans wind turbines, we successfully measured and isolated wind turbine-generated noise.

Through a spectral analysis of the noise recordings, we obtained sound pressure level data demonstrative of the wind turbine-generated ILFN. In this report, we discuss the manner in which the data were obtained and present and analyze the study results.

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[5] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

[6] Infrasound is defined as sound at frequencies less than 20 Hz. The focus of this report is frequencies less than 40 Hz, which includes low frequency sound as well.

WIND TURBINE DETAILS

Kumeyaay Wind Farm

Kumeyaay Wind is owned by Infigen Energy of Australia and operated by Bluarc Management of Texas, on 45 acres of land on the Campo Indian Reservation in southeastern San Diego County.[7] The nearest community outside of the tribal land is Boulevard, California. Currently there are 25 wind turbines operating at this facility. The wind turbines are located on a north-south ridge (Tecate Divide) at elevations ranging from 4,200 to 4,600 feet. The turbines started generating power in December 2005.

Kumeyaay Wind's turbines are Gamesa model G87X-2.0, with a rated power of 2.0 megawatts (MW). According to the manufacturer's published data, the G87X-2.0 has a hub height (height of the nacelle, which houses the gearbox, transmission and generator) that can vary from 217 to 325 feet depending on site conditions. The manufacturer also represents that the turbine has a rotor diameter of 283 feet, with three 138-foot-long, adjustable pitch blades. According to Councilman Miskwish the hub height of the Kumeyaay Wind turbines is typically 228 feet, and the blades are 145 feet long. Figure 1 shows some of the wind turbines.

The G87-2.0 model has a reported cut-in wind speed of 8.9 mph (5 mph according to former Campo tribal Councilman Miskwish, a.k.a. Michael Connolly) and achieves its rated (max) power generation at about 31 mph. The operational speed of the turbines is reported by the manufacturer to be in the range of 9 to 19 revolutions per minute (rpm) depending on wind conditions.

Figure 1 Wind Turbines at Kumeyaay Wind

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[7] "Kumeyaay Wind Energy Project," PowerPoint presentation by Councilman Michael Connolly Miskwish, Campo Kumeyaay Nation, November 30, 2008., *available here:* http://www.certredearth.com/pdfs/Presentations/2007/KumeyaayWindEnergyProjectCampoKumeyaayNation.pdf

Ocotillo Wind Energy Facility

The Ocotillo Wind facility is owned and operated by Pattern Energy, on 10,200 acres of federal land located in southwestern Imperial County and managed by the United States Bureau of Land Management (BLM). Ocotillo Wind currently has 112 operating wind turbines. The wind turbines are located on the desert floor adjacent to the community of Ocotillo, California, at elevations ranging from approximately 300 to 1,400 feet above sea level. The Ocotillo Wind turbines are Siemens model SWT-2.3-108, with a rated power of 2.3 MW. Figure 2 shows some of Ocotillo Wind's turbines.

According to the manufacturer's published data, the SWT-2.3-108 model has a nominal hub height of 260 feet depending on site conditions, with a turbine rotor diameter of 351 feet and three 172-foot-long blades. The SWT-2.3-108 has a manufacturer-reported cut-in wind speed between 6.6 and 8.9 mph and achieves its rated power at wind speeds between 24 and 27 mph. The operational speed of the turbines reported by the manufacturer is in the range of 6 to 16 rpm depending on wind conditions.

Figure 2 Wind Turbines at Ocotillo Wind

MEASUREMENT LOCATIONS

Kumeyaay Wind-Area Residences

Both indoor and outdoor noise recordings were made at six residences in the Boulevard area near the Kumeyaay Wind turbines.

Table 1 lists the addresses of the residences at which the measurements were taken, along with the dates and times of the recordings. A map showing the Kumeyaay Wind-area measurement locations is provided in Appendix A.

Table 1 Addresses of Residences Used in Kumeyaay Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
D. Elliott	Off of Crestwood, Campo Indian Reservation	2,960 feet	April 28	16:02	16:22
			April 30	11:00	11:20
G. Thompson	33 Blackwood Road, Manzanita Indian Reservation	2,880 feet	April 28	18:47	19:07
R. Elliott	25 Crestwood Road, Manzanita Indian Reservation	4,330 feet	April 28	17:30	17:50
D. Bonfiglio	40123 Ribbonwood Road, Boulevard	2.9 miles	April 29	9:15	9:35
K. Oppenheimer	39544 Clements Street, Boulevard	1.6 miles	April 30	15:11	15:31
M. Morgan	2912 Ribbonwood Road, Boulevard	1.7 miles	April 30	16:15	16:35
D. Tisdale	Morning Star Ranch, San Diego Co.	5.7 miles	April 30	13:45	14:05

[1] Recordings were nominally 20 minutes long

The Kumeyaay Wind-area residences at which we took measurements are located at distances of 2,880 feet to 5.7 miles from the nearest wind turbine at Kumeyaay Wind Farm. Additional recordings were made at two reference locations, which were closer to the wind turbines than the residential locations, as shown below in Table 2.

A recording was also obtained at the Tisdale ranch located 5.7 miles from the nearest wind turbine (see Table 1 above). The purpose of this recording was primarily to document existing ambient conditions; however, even at that great distance, analysis of the data indicates the presence of noise generated by the existing turbines.

A recording was also made at one of the guest cabins at the Live Oak Springs Resort. The purpose of this latter measurement was to obtain noise recordings in a condition with essentially no "local wind." By no local wind, it is meant that the wind at the microphone was either very light or non-existent even though there was wind at the wind turbine level, which was confirmed by observing the closest wind turbine rotating, thus providing a sample of wind turbine noise that was minimally affected by wind on the microphone. This latter recording was made at 10:10 pm on April 28. Cabin #2 at Live Oak Springs Resort is 5,950 feet from the nearest wind turbine.

Kumeyaay Reference Noise Measurements

To more fully document wind turbine-generated noise levels and spectra, we took noise measurements at locations closer to the subject wind turbines than the residences used in this study. Two reference locations were used near Kumeyaay Wind. Table 2 indicates the locations, distances to the closest wind turbine, dates and times of the reference recordings.

Table 2 Reference Locations for Kumeyaay Wind

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Kumeyaay (K-R1)	2,040	April 28	15:58	16:18
Kumeyaay (K-R2)	930	April 30	11:00	11:20

[1] Recordings were nominally 20 minutes long

The recording on April 28 at 10:00 pm at Live Oak Springs Resort (K-LOSR) also serves as a reference measurement.

Ocotillo Wind-Area Residences

Recordings were made at three Ocotillo residences near the Ocotillo Wind turbines. Table 3 lists the addresses of the residences at which the measurements were taken, along with the dates and times of recordings. A map showing the Ocotillo Wind-area measurement locations is provided in Appendix A.

Table 3 Addresses of Residences Used in Ocotillo Measurements

Resident/Owner	Address	Distance to Closest Wind Turbine	Date	Recording Start Time	Recording End Time[1]
J. Pelly	1362 Shell Canyon Road, Imperial County	3,220 feet	April 29	11:22	11:42
				20:00	20:20
P. Ewing	98 Imperial Highway, Ocotillo	3,590 feet	April 29	12:32	12:52
				21:00	21:20

D. Tucker	1164 Seminole Avenue, Ocotillo	1.2 miles	April 29	13:42	14:02
				22:20	22:40

[1] Recordings were nominally 20 minutes long

The Ocotillo Wind-area residences at which we took measurements are located at distances of 3,220 feet to 1.2 miles from the closest wind turbine at Ocotillo Wind. We also made measurements at three reference locations closer to the wind turbines, as shown in Table 4 below.

Ocotillo Reference Noise Measurements

We used three reference locations near Ocotillo Wind. Table 4 lists the locations, distance to the closest wind turbine, dates and times of the reference recordings.

Table 4 Reference Locations for Ocotillo

Location	Distance to Closest Wind Turbine (feet)	Date	Recording Start Time	Recording End Time[1]
Ocotillo (O-R1)	1,540	April 29	11:19	11:39
			20:00	20:20
Ocotillo (O-R2)	1,470	April 29	13:44	14:04
			21:30	21:50
Ocotillo (O-R3)	2,100	April 29	22:08	22:28

[1] Recordings were nominally 20 minutes long

NOISE RECORDING METHODOLOGY

We made all of the noise recordings with Brüel and Kjaer (B&K) type-4193, ½-inch, pressure-field microphones, which are specifically designed for infrasound measurement and provide a linear response from 0.07 cycles per second (Hz) to 20,000 Hz. A B&K type-UC-0211 adapter was used to couple the microphones to a B&K type-2639 preamplifier, providing a linear frequency response down to 0.1 Hz for the microphone/adaptor/preamplifier system. All recordings were calibrated with B&K type-4230 calibrators, which are checked and adjusted with NIST traceable accuracy with a B&K type-4220 pistonphone in the WIA laboratory in Emeryville, California.

We recorded all the noise samples with a TEAC LX10, 16-channel digital recorder, which provides a linear frequency response (i.e., ±0.1% or less) to a lower frequency limit of essentially 0.1 Hz when used in the "AC mode" (which we did). Twenty minute (nominal) noise recordings were made at each location. Using two different microphones, recordings were made simultaneously both indoors and outdoors at each subject residence. This same approach was also used in the Shirley Wind Farm study[8].

Using a third microphone and another recorder (SONY PCM D-50 digital recorder), recordings were made at reference locations closer to the wind turbines while the residential recordings were in progress. The frequency response of this third system is linear down to a frequency of 1.4 Hz, being limited by the SONY recorder.

For several of the residential and reference locations, recordings were repeated at a different time and/or date. All measurement data reported herein are based on an analysis of the noise recordings played back in the WIA laboratory.

Residence Location Measurements

For measurements conducted at the residences, a microphone was set up inside each residence mounted on a tripod at 4.5 feet above the floor, typically in the middle of the room. The indoor recordings were made in either the living room (mostly) or dining room of the residences. Indoors, the microphone was oriented vertically and covered with a 7-inch-diameter wind screen. Figure 3 shows the microphone and windscreen mounted on a tripod inside one of the residences.

A second microphone was set up outside of each residence. Following IEC Standard 61400-11, the outside microphone was rested horizontally (i.e., flush mounted) on a ½-inch-thick plywood "ground board" that is 1 meter in diameter. The microphone was oriented in the direction of the nearest visible wind turbine and the ground board was placed in a flat location between the residence and the wind turbines.

Also following IEC 61400-11, wind effects on the outdoor microphone were reduced using both a hemispherical 7-inch-diameter primary windscreen placed directly over the microphone, and a hemispherical 20-inch-diameter secondary windscreen placed over the primary windscreen and mounted on the ground board. The microphone and primary windscreen were placed under the center of the secondary windscreen.

The primary windscreen was cut from a spherical, ACO-Pacific foam windscreen with a density of 80 pores per inch (ppi). The secondary windscreen was constructed by WIA using a wire frame covered with ½ inch open wire mesh. A one-inch-thick layer of open cell foam with a density of 30 ppi was attached to the wire mesh. Figure 4 shows the outdoor microphone, secondary windscreen, and ground board outside one of the residences.

Both microphones used at the residences were powered by B&K type-2804 power supplies, with signals amplified by a WIA type-228 multi-channel measurement amplifier, and recorded on a TEAC LX10 16-channel digital data recorder. Inside and outside noise signals were recorded simultaneously to allow for correlation of interior and exterior sound levels during analysis.

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[8] Channel Islands Acoustics, et al, A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin, Report No. 122412-1, December 24, 2012.

Figure 3 Microphone Inside Residence

Figure 4 Microphone Outside Residence

Reference Location Measurements

A third B&K 4193 microphone was used to obtain simultaneous reference measurements at locations closer to the wind turbines during each of the residential measurements. This third microphone was powered by a B&K type-5935 power supply and amplifier, with the signal recorded on a Sony type PCM D-50 recorder. The same windscreen and ground board configuration (i.e., primary and secondary windscreen) used for the residential recordings, was also used for the reference locations. Reference measurements were obtained at different locations at each of the two facilities. Figure 5 shows the microphone, ground board and secondary windscreen at one of the reference measurement locations in Ocotillo.

Figure 5 Reference Location O-R2 with Microphone, Ground Board and Windscreen

NOISE MEASUREMENT BACKGROUND

Purpose of Measurements

The primary purpose of making the wind turbine noise measurements reported herein was to determine whether, and at what levels and under what conditions, the Kumeyaay Wind and Ocotillo Wind turbines generate ILFN, and how far the ILFN is propagated. In light of increasing evidence in the literature that ILFN can affect and harm humans[9] [10] [11] [12] [13], along with numerous complaints of health impacts from both Boulevard- and Ocotillo-area residents[14] since the wind turbines near their respective residences began operating, we had a subsidiary goal to obtain measurements that accurately show the pressure fluctuations in the sound, so as to allow an accurate and robust analysis of the human health and environmental impacts of the ILFN generated.

Noise Measurements in Presence of Wind

Some atmospheric pressure fluctuations are oscillatory in nature, whereas others are not. An example of a non-oscillatory pressure fluctuation is a change in barometric pressure; a change that occurs over a much longer time scale (e.g., hours) than the fluctuations being measured in this study. Wind and, in particular, gusts of wind cause another form of non-oscillatory pressure fluctuation, though it occurs on a much shorter time scale (e.g., fraction of a second). Local wind can cause a pressure change affecting the human ear similar to the pressure change that occurs in an airplane as it ascends or descends during takeoff and landing, but this pressure change is not sound.

Sound, in contrast to non-oscillatory fluctuations, consists of regular oscillatory pressure fluctuations in the air due to traveling waves. Sound waves can propagate over long distances depending on many factors. In the case of noise generated by machinery, the pressure fluctuations can be highly periodic in nature (i.e., regular oscillations). Sound that is characterized by discrete frequencies is referred to as being tonal. Although wind can generate sound due to turbulence around objects (e.g., trees, buildings), this sound is generally random in nature, lacks periodicity and is usually not in the infrasound range of frequencies.

However, the sound measurements we were interested in for this study (i.e. periodic wind turbine-generated ILFN) can be greatly impacted by non-oscillatory pressure fluctuations and extraneous noise caused by, for example, wind turbulence due to steady wind and particularly during gusts. The microphones we used in these measurements are highly sensitive instruments, with pressure sensor diaphragms that will respond to any rapid enough pressure change in the air regardless of the cause. To minimize the artificial (i.e. unrelated to the noise source being measured) noise or "pseudo sound" caused by wind gusts and other pressure fluctuations not associated with the wind turbine-generated noise itself, we employed special procedures. The

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[9] Salt, A.N., T.E. Hullar, Responses of the ear to low frequency sounds, infrasound and wind turbines, Hearing Research, 16 June 2010.

[10] Salt, A.N., J.T. Lichtenhan, Reponses of the Inner Ear to Infrasound, Fourth International Meeting on Wind Turbine Noise, Rome, Italy, April 2011.

[11] Salt, A.N., J.A. Kaltenbach, Infrasound from Wind Turbines Could Affect Humans, Bulletin of Science, Technology & Society, 31, 296-302, 2011.

[12] Salt, A.N., J.T. Lichtenhan, Perception-based protection from low-frequency sounds may not be enough, Inter-Noise 2012, New York, New York, August 2012.

[13] Lichtenhan, J.T., A.N. Salt, Amplitude Modulation of Audible Sounds by Non-Audible Sounds: Understanding the Effects of Wind-Turbine Noise, Proceedings of JASA, 2013.

[14] San Diego Reader, Volume 42, Number 34, August 22, 2013.

main sources of artificial noise and the procedures we used to minimize its impact are discussed more fully below.

Artificial Noise due to Turbulence at the Microphone

One source of artificial noise caused by wind on the microphone – and the most commonly encountered artificial noise source in outdoor noise measurements – is the turbulence caused by wind blowing over the microphone. To minimize this effect of wind when conducting environmental noise measurements outdoors, it is standard practice to use a windscreen,[15] the size of which is usually selected based on the magnitude of the wind encountered. The higher the wind speed generally the larger the windscreen required to minimize artificial noise caused by air turbulence at the microphone.

The windscreen used must be porous enough so as not to significantly diminish the pressure fluctuations associated with the noise being measured, which is to say that the wind screen must be acoustically transparent. As indicated above, the measurements reported herein followed procedures on windscreen design and usage as recommended by IEC 64100-11.

Artificial Noise due to Air Gusts

There is another – and more problematic – source of artificial wind-based noise. This one is caused by non-oscillatory pressure fluctuations associated with wind gusts as well as the pressure associated with the air flow in a steady wind. Air gusts can have an effect on a microphone signal in two ways. Outdoors, the microphone diaphragm will respond to the direct change in pressure associated with air flow; whereas indoors, the microphone will respond to the indirect change in pressure associated with wind and particularly gusts of wind that pressurize the interior of the building. These wind effects induce artificial noise that appears in the electrical signal generated by the microphone that is in the ILFN frequency range. This pseudo noise can, in turn, affect the spectral analysis of the recorded data. This form of pseudo noise (i.e., pressure changes due to air flow) is not substantially reduced by the use of a windscreen or even multiple windscreens generally regardless of their size.

Here, as discussed more fully in the Method of Analysis of Recorded Data section below, we analyzed the sound recordings in this study using a fast Fourier transform (FFT) technique to resolve low frequency and infrasound data. The primary range of interest in these measurements was in frequencies between 0.1 and 40 Hz. An FFT analysis produces a constant bandwidth (B). A 400-line FFT was used in the analysis, which means the bandwidth was $B = 0.1$ Hz. This allows resolution of frequency components to fractions of one Hz.

When using a very narrow bandwidth (e.g., 0.1 Hz), the time required for filtering is long in order to obtain the frequency resolution. The FFT analysis time T required for a specific bandwith B is given by: $T = 1/B$. For a 0.1 Hz bandwidth the time required is 10 sec. At this time scale, the effects of air pressure changes due to air movement tend to linger in the filtering process as discussed in the Method of Analysis of Recorded Data section below.

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[15] ANSI S12.9-2013/Part 3, Quantities and Procedures for Description and Measurement of Environmental Sound, Part 3: Short-Term Measurements with an Observer Present, American National Standards Institute, 2013.

To reduce the wind gust-induced artificial noise that manifests in the data with such long filtering times, both physical means during recording and analytical post-recording methods can be employed to minimize this artificial noise. The most effective pre-measurement technique is to dig a hole in the ground and put the microphone into it.[16] If two pits and microphones are used, then a cross-spectral analysis is also possible. In this study, however, it was impractical and, in some cases, impossible to dig microphone pits at the 15 total measurement locations. We thus relied on post-measurement analytical methods to filter out the pseudo noise as much as possible.

Each of the two most effective analytical techniques takes advantage of the fact that wind turbines and other large rotating machinery with blades (e.g., building ventilation fans and helicopters) produce very regular, oscillatory pressure fluctuations that are highly deterministic,[17] whereas pressure changes due to air movement associated with local wind gusts are essentially random in nature. The sound produced by wind turbines is tonal in nature, meaning that it has a spectrum with discrete frequencies that, in this case, are interrelated (i.e., harmonics of the blade passage frequency). This difference between the random wind noise and the wind turbine noise provides a means to minimize the latter in the signal processing of the recorded data. It has been posited that it is the tonal nature of wind turbine infrasound that may have some influence on residents in the vicinity of large wind turbines[18].

The artificial noise associated with pressure changes at the microphone due to local wind gusts can be minimized in two ways when analyzing the recorded signal. The first technique is to average the noise measurements over a longer time period. This tends to reduce the effect of pseudo noise associated with random air pressure transients during wind gusts, but does not affect the very regular, periodic pressure fluctuations generated by wind turbines.

When averaging over time is not sufficient, a second technique can be used to further minimize the effect of random pressure fluctuations associated with local wind. This second technique uses "coherent output power," a cross-spectral process. Both time averaging and coherent output power are discussed below under the method of analysis of recorded data.

WIND TURBINE OPERATION DURING MEASUREMENTS

Video recordings were made several times during the study period to document the operation of the wind turbines. Using the video recordings, we determined both the rotational speed of the wind turbine rotors (Ω in rpm) and the so-called "blade passage frequency" (f_0, also referred to as "blade passing frequency" or BPF), which is calculated in cycles per second, where $f_0 = N \times \Omega / 60$, and N is the number of blades. For a three-bladed rotor ($N = 3$) the blade passage frequency is given by the equation:

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[16] Betke, L. and H. Remmers, Messung and Bewertung von tieffrequentem Schall, Proceedings of DAGA 1998 (in German)

[17] Johnson, Wayne, Helicopter Theory, Dover Publications, New York, 1980.

[18] Hessler, G., P. Schomer, Criteria for Wind-turbine Noise Immissions, Proceedings of the Meetings on Acoustics ICA 2013, Montreal, 2-7 June 2013, Acoustical Society of America, Vol. 19, 040152 (2013).

$$f_0 = \frac{\Omega}{20} .$$

Associated with the blade passage frequency are harmonics, which are integer multiples of the blade passage frequency. In this study, we typically observed at least five discrete harmonics in the measurement data. This pattern was also observed in the aforementioned Shirley Wind Farm study.

The harmonic frequencies are given by:

$$f_n = (n + 1) \times f_0 , where\ n \geq 1 .$$

For example, if Ω = 17 rpm, then f_0 = 0.85 Hz and the frequencies of the first six harmonics (n = 1 through 6) are: 1.7, 2.6, 3.4, 4.3, 5.1 and 6.0 Hz.

Table 5 summarizes a selection of the wind turbine speeds observed during the recordings. We note that the turbine speed of 16.2 rpm observed in Ocotillo at 19:51 on April 29 is the maximum rated speed for the Siemens SWT-2.3-108.

Table 5 Rotational Speeds Observed for Nearest Wind Turbines

Facility	**Date**	**Location**[1]	**Time**	**Speed (rpm)**	**BPF (Hz)**
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 28	D. Elliott	14:14	17.3	0.87
			15:05	17.1	0.86
			16:29	16.8	0.84
			16:30	16.3	0.81
		R. Elliott	17:28	16.7	0.83
		Thompson	19:32	17.2	0.86
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 29	Bonfiglio	9.37	12.2	0.61

Ocotillo Wind (Siemens Turbines – rated speed of 6 to 16 rpm)	April 29	O-R1	11:26	9.8	0.49
			11:29	7.4	0.37
			11:32	6.5	0.32
		O-R2	12:40	13.3	0.67
			13:54	15.0	0.75
			14:02	12.5	0.63
		O-R1	19:51	16.2	0.81
Kumeyaay Wind (Gamesa Turbines – rated speed of 9 to 19 rpm)	April 30	D. Elliott	10:33	15.6	0.78
		K-R2	11:22	16.7	0.83
			11:24	13.6	0.68
		Tisdale	13:45	14 to 16.6[2]	0.7 to 0.83[2]
		Oppenheimer	14:50	16.7	0.83
			15:17	17.1	0.86
			15:27	16.7	0.83
		Morgan	16:12	17.1	0.86
			16:18	16.2	0.81
			16:28	17.1	0.86

[1] Locations refer to where video was recorded

[2] Based on observed rotor speeds before and after recording

METEOROLOGICAL DATA

Weather Underground provides publicly available weather data for the two measurement areas (Boulevard and Ocotillo) on its website (wunderground.com). Among other things, this data includes wind speed, wind direction, temperature, and pressure. Weather Underground reports that it measures the meteorological conditions for Boulevard and Ocotillo at respective elevations of 4,113 feet and 694 feet above sea level. The relevant Weather Underground weather data for the Boulevard and Ocotillo areas is provided in Appendix B and summarized below.

Meteorological Data for the Kumeyaay Wind-Area Noise Measurements

We obtained noise measurements in the vicinity of the Kumeyaay Wind turbines on two different days. We took measurements on April 28, 2013, in the mid-afternoon to early evening. On April 30, we took measurements from mid-morning to mid-afternoon.

April 28, 2013

The Weather Underground data for this date show wind from the northwest in the morning, shifting to the west in the afternoon when the noise recordings were made. Average wind speeds between 1pm and 7pm were approximately 15 mph, with some gusts reaching 25 mph.

April 29, 2013

The Weather Underground data for this date show that wind speeds were considerably lower than on April 28, typically averaging between 5 and 8 mph, with some gusts reaching 10 mph. The wind direction between 9 am and 10 am, when the lone Kumeyaay Wind-area noise recording on this date was made, was from west south west.

April 30, 2013

The Weather Underground data for this date show that the wind direction in the morning was from the west, with average wind speeds that were 5 mph or less during the second recording at Mr. Elliott's residence. In the afternoon, during recordings at the Oppenheimer, Morgan and Tisdale residences, the wind was from the southwest, with average wind speeds between 10 and 17 mph and gusts up to 25 mph.

Meteorological Data for the Ocotillo Wind-Area Noise Measurements

We took noise measurements only on April 29, 2013, for the Ocotillo Wind Energy Facility. We took measurements from mid-morning to mid-afternoon, and then again from early evening to late evening.

April 29, 2013

The Weather Underground data for this date show that between 11am and 2 pm the wind direction was from the southwest with average wind speeds between 10 and 15 mph, with gusts from 15 to 20 mph. In the evening, the wind was also from the southwest, but was much stronger, with average wind speeds between 15 and 25 mph and gusts up to 35 mph.

METHOD OF ANALYSIS OF RECORDED DATA

We analyzed the 20 minute (nominal) recordings in the WIA laboratory with a Larson Davis type-2900 2-channel FFT analyzer. We first viewed each recorded sample in digital strip chart format to visually locate periods of lower local wind gusts to minimize low-frequency wind pressure transient effects on the data. We set the FFT analyzer for 40-Hz bandwidth, with 400-line and 0.1-Hz resolution. We used linear averaging. A Hanning window was used during a one- to two-minute, low-wind period to obtain an "energy average" with maximum sampling overlap. We stored the results for each sample, including autospectra, coherence, and coherent output power for both channels of data at the residential locations (i.e., indoors and outdoors). We also obtained autospectra for the reference locations.

Autospectra and Coherent Output Power

One of the strengths of our indoor-outdoor sampling design is that it made possible the use of what is called the "coherent output power" to filter out of the data the effect of the low-frequency wind pressure transients caused by local wind gusts. If two closely correlated signals are available (such as we have here, with the indoor and outdoor measurements for each residential study location), it is possible to use the coherent output power to reduce the effects of uncorrelated or weakly correlated phenomenon associated with wind gusts.

Coherent output power is based on use of the coherence between two signals to weight the spectra of one of the signals based on coherent frequency components common to the two simultaneously recorded signals. Where, as here, the wind turbine-generated noise remains at fairly consistent frequencies over the recording periods, the effects on the recorded signal of the essentially random, non-oscillatory pressure fluctuations caused by wind gusts should be reduced using this analysis procedure. The result is sometimes referred to as the coherent output spectrum.[19] For an example of previous studies that have used coherent output power to obtain wind turbine noise spectra, see Kelley, et al. (1985).[20]

In discussing coherent output power we use standard signal processing terminology. Obviously, all of the terms are functions of frequency.

For two signals (signal 1 and signal 2), the coherent output power for signal 2 (i.e., G_2) is defined as:

$$G_2 = {\gamma_{12}}^2 G_{22} .$$

The term ${\gamma_{12}}^2$ is the coherence (also referred to as spectral coherence) between the two signals and the term $G_{22}$is the autospectral density of the second signal. The value of the coherence lies in the range of $0 \le {\gamma_{12}}^2 \le 1$. A value of ${\gamma_{12}}^2 = 1$ indicates there is a one-to-one correlation between the two signals, which could only occur within an ideal system. In practice, ${\gamma_{12}}^2$ will generally be less than 1.

The coherence is defined as:

$${\gamma_{12}}^2 = \frac{|G_{12}|^2}{G_{11} G_{22}}$$

The term autospectral density used here has the same meaning as sound pressure level spectrum, the units of which are dB (re: 20 μPa). The term G_{11} is the autospectral density of the first signal.

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[19] Bendat, J. and A. Piersol, Random Data – Analysis and Measurement Procedures, 2nd Edition, John Wiley & Sons, 1986.

[20] Kelley, N.D., et al., Acoustic Noise Associated with the MOD-1 Wind Turbine: Its Source, Impact and Control, SERI/TR-635-1166 report prepared for U.S. Department of Energy, Solar Energy Research Institute, February 1985.

The term G_{12} is the cross-spectral density between the two signals, and the term $|G_{12}|^2$ is the square of the magnitude of the cross-spectral density.

For two recorded signals, it is possible to determine the coherence of the first with respect to the second (γ_{12}) and switch the two and determine the coherence of the second with respect to the first (γ_{21}). Consequently it is possible to obtain an inside coherent output power spectrum and an outdoor coherent output power spectrum. The measurement data presented herein indicate when the data are the autospectra, and when they are determined from the coherent output power. Where coherence data are presented, it is the coherence of the indoor signal with respect to that of the outdoor signal.

Sound Level Corrections Due to Use of Ground Board

Placing an outdoor microphone on a ground board, as was done in this study, results in higher sound pressure levels (up to 3 dB greater) for frequencies in the range of 50 to 20,000 Hz when compared to those measured at 4.5 to 5.5 feet above the ground, a standard height used to make environmental noise measurements as indicated in ANSI S12.9-2013/Part 3. Consequently corrections to the sound level data at frequencies greater than 50 Hz obtained using a ground board would be required.

However, for frequencies less than 50 Hz, the sound pressure level at the ground surface is essentially the same as that at a height of 5 feet. This is because a microphone on a tripod 5 feet above the ground is at a height less than one-fourth the wavelength of the sound at this frequency (i.e., $0.25 \times \lambda_{50\,Hz} = 0.25 \times \frac{1{,}100}{50} = 5.5\,feet$) and there is little difference at frequencies less than 50 Hz between the sound field at ground level and the sound field at 5 feet above the ground. This fact has been confirmed by other measurements[21].

Because the data presented herein are in the ILFN range with frequencies less than 40 Hz, no corrections to the sound level data are necessary, even though the measurements were made with a ground board.

NOISE MEASUREMENT RESULTS

Noise Data for Kumeyaay Wind

The noise spectra data from the Kumeyaay Wind-area measurements are provided in Appendix C. The turbine blade passage frequencies – in the range of 0.7 to 0.9 Hz (see Table 5) – and their harmonics up to 5 Hz are evident in the sound spectra from both recording days. Indeed, they align almost exactly with the predominant spectral peaks. This is a very strong indication that the wind turbines produced the ILFN at those frequencies.

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[21] Hansen, K., Z. Branko, C. Hansen, Evaluation of Secondary Windshield Designs for Outdoor Measurements of Low Frequency Noise and Infrasound, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

Data for Live Oak Springs Resort, Cabin #2 (K-LOSR)

It is instructive to first examine the spectra obtained at the Live Oak Springs Resort where there was virtually no local wind during the recording even though there was wind at the turbines as determined from observing the closest turbine rotating at the time. Live Oak Springs Resort is somewhat sheltered from wind, but has a direct line of sight to the closest wind turbine at a distance of 5,950 feet.

Looking at Figure C-1, it is evident in the autospectra for both indoor and outdoor measurements that the discrete frequencies predominating in the infrasound range correspond to the blade passage frequency of the nearest wind turbine (0.8 Hz) and its first five harmonics (1.6, 2.4, 3.2, 4.1 and 4.9 Hz). A blade passage frequency of 0.8 Hz corresponds to a rotational speed of 16 rpm. We note that the indoor levels at these frequencies are slightly higher than the outdoor levels, an indication of possible amplification associated with the building structure.

Figure C-2 presents the two coherent output power spectra and the coherence of the indoor to outdoor signals. At the blade passage frequency (0.8 Hz) and in the range of 1.6 to 5 Hz (including the first five blade passage frequency harmonics of 1.6, 2.4, 3.2, 4.1 and 4.9 Hz), the coherence is 0.75 or greater, indicating a strong correlation between indoor and outdoor sound levels.

A high coherence indicates that two signals are strongly correlated and contain the same frequency content. This is exactly what one would expect from a large rotating mechanical device such as a wind turbine that produces a steady, tonal (periodic) sound, whereas the effects of wind are very random in particular concerning signals from two different microphones, one of which is indoors. Hence, the correlation of the wind effects in the indoor and outdoor signals should be weak for the random effects of the wind. Thus there will be a low coherence associated with the wind and its effects on the two different signals. Averaging the total microphone signal over time and weighting the result by the coherence results in a diminished contribution from the wind, because of the low coherence of the wind effects.

Figure C-3 compares the autospectrum with the coherent output spectrum for the indoors measurement at Live Oak Springs Resort. It shows a very close match over the frequency range of 0.8 to 5 Hz at the discrete frequencies associated with the wind turbine ILFN.

Inside the guest cabin at Live Oak Springs Resort, sound pressure levels in the infrasound range measured between 45 and 49 dB. The outside sound pressure levels were somewhat lower in the ILFN range, seeming to indicate an amplification occurring from outside to inside, which became even more pronounced in the range of 5 to 8 Hz. There is also a strong peak at 26.4 Hz, which may be caused by an "amplitude modulation" similar to that identified in the Falmouth wind turbine study[22]. The coherence at this frequency is 0.95. Amplitude modulation occurs when a low frequency signal causes the level of a higher frequency signal to fluctuate. This fluctuation occurs at the frequency of the lower frequency signal. This has been the subject of many complaints concerning wind turbine noise[23] [24].

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[22] Ambrose, S. and R. Rand, The Bruce McPherson Infrasound and Low Frequency Noise Study, 14 December 2011.

[23] Gabriel, J., S. Vogl, T. Neumann, Amplitude Modulation and Complaints about Wind Turbine Noise, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

The ILFN levels at Live Oak Springs Resort's guest Cabin #2 would have been even greater if the cabin were closer to the nearest Kumeyaay Wind turbine than it is – 1.1 miles, or 5,950 feet. The ILFN levels would have also been greater under different wind conditions. According to the Weather Underground report for Boulevard, at the time we measured the noise at the guest cabin – starting at 10:10 pm on April 28 – the wind was blowing from the west with an average speed of approximately 7 mph and gusts up to 12 mph, which is at the lower end of the operating conditions for the Gamesa wind turbines. Because the closest wind turbine is north-northeast of the cabin, the cabin was crosswind and somewhat upwind of the turbine and thus receiving lower levels of turbine-generated noise than locations downwind of the turbines.

Data for Dave Elliott's Residence

Like the Live Oak Springs Resort guest cabin measurements, the April 30 (11 am) measurements at Dave Elliott's residence show pronounced peaks in the autospectra at frequencies corresponding to the blade passage frequency of the nearest wind turbine (0.78 Hz) and the first five harmonics. The inside level at 0.78 Hz was 54 dB. In this case, as displayed in Figure C-4, the sound levels were slightly higher inside than outside at 1.6 and 2.4 Hz. Above 3 Hz the inside levels were lower than outside. The maximum inside sound level of 59 dB occurred at 1.6 Hz (the first harmonic of the blade passage frequency).

Data for Ginger Thompson's Residence

As shown in the autospectrum in Figure C-5, the April 28 (6:50 pm) measurements at Ginger Thompson's residence demonstrate a similar discrete frequency pattern between 0 and 5.2 Hz that corresponds to the blade passage frequency of the nearest turbine (0.80 Hz) and the first three associated harmonics (1.6, 2.4, and 3.2 Hz), which corresponds to a rotational speed of 16.0 rpm. The lowest frequency peak in the spectrum occurs somewhat lower (i.e., at 0.78 Hz) than the blade passage frequency; a phenomenon seen in some of the other measurement data.

As also seen at Mr. Elliott's residence and at most other study sites, the measured ILFN levels at Ms. Thompson's residence were amplified indoors, with the inside levels higher than outside levels throughout the frequency range. The maximum inside sound level of 60 dB occurred at just below the blade passage frequency of 0.80 Hz.

Data for Rowena Elliott's Residence

In the April 28 (5:30 pm) measurement data from Rowena Elliott's residence, shown in Figure C-6, the autospectra peaks corresponding to WT infrasound from Kumeyaay protrude above the general wind noise spectrum. The inside coherent output power spectrum is also plotted in Figure C-6 with most of the same peaks that appear in the autospectrum. Also present in the spectrum is a peak at 1.0 Hz, which does not correspond to any of the harmonics of the BPF observed in Kumeyaay at that time. We suspect that this infrasound is coming from the wind turbines at Ocotillo Wind, which are 15 to 20 miles away. This peak would correspond to a BPF

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[24] Stigwood, M., S. Large, D. Stigwood, Audible Amplitude Modulation – Results of Field Measurements and Investigations Compared to Psycho-acoustical Assessment and Theoretical Research, 5th International Conference on Wind Turbine Noise, Denver, 28-30 August 2013.

of 0.5 Hz, which would be consistent with the somewhat slower rotational speeds for the WTs in Ocotillo. Detecting WT infrasound from 15 to 20 miles away is not surprising. Metelka[25] for example has measured WT infrasound at a distance of 77 miles from its source. The maximum inside sound level of 53 dB occurred at 1.6 Hz, the first harmonic of the Kumeyaay BPF (0.8 Hz).

Data for Kenny Oppenheimer's Residence

As with the data for the previously discussed measurement locations, the April 30 (3:11 pm) measurement data for Kenny Oppenheimer's residence, shown in Figure C- 7, reveal sound pressure level peaks at the blade passage frequency of the nearest wind turbine (0.9 Hz) and its first three harmonics (1.8, 2.7 and 3.6 Hz). There is also a strong peak both indoors and outdoors at 13.6 Hz whose source, in contrast to the wind turbine-generated ILFN peaks at the blade passage frequency and its first three harmonics, we have been unable to identify. In this case, however, the outside sound levels were much greater than those inside the residence. The highest outside sound level was 57 dB and occurred at the blade passage frequency of 0.9 Hz. By contrast, the highest indoor sound level in the coherent output power spectrum was 44 dB, also at 0.9 Hz.

We have estimated the WT infrasound inside at 0.9 Hz to be approximately 51 dB using the coherent output power spectrum level and correcting for the coherence at that frequency. This seems to indicate that the residence is attenuating the wind turbine infrasound more substantially than at some of the other residences investigated, which could be due to a much more tightly sealed building envelope and/or a more substantial exterior wall construction. This effect was also evident in the data for one of the Ocotillo residences.

As a result of this disparity, the coherence of the indoor and outdoor ILFN signals is not as great as with closer measurement locations, including the Live Oak Springs Resort guest cabin and the residences of Mr. Elliott, Ms. Thompson and Ms. Elliott. Nonetheless, the coherence of the two signals at the blade passage frequency and its first three harmonics is still relatively strong, at 0.5 or greater. This evinces a definite correlation between outdoor and indoor sound levels even at great distance from the wind turbine noise source. Also evident in the data is a peak at 13.7 Hz. The may be caused by amplitude modulation.

Data from Marie Morgan's Residence

The April 30 (4:20 pm) measurement data from Marie Morgan's residence, including the inside and outside coherent output power spectra, are shown in Figure C-8. Like the data measured at the residences of Mr. Elliott, and Ms. Thompson, the data at Ms. Morgan's residence show higher levels of ILFN indoors than outdoors.

And like the data measured at Ms. Elliott's residences, there appear to be multiple – in this case three – different BPFs in the data. The lowest BPF, similar to the data measured at Ms. Elliott's residence, appears to be infrasound coming from Ocotillo Wind (i.e., BPF1 of 0.39 Hz). Above that frequency there are two BPF which are associated with Kumeyaay WTs. Note that not all

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[25] Metelka, A., Narrowband low frequency pressure and vibration inside homes in the proximity to wind farms, presentation at the 166th Meeting: Acoustical Society of America, San Francisco, 4 December 2013.

Kumeyaay WTs could be observed, and it is possible that some could be operating at a speed of 14 rpm and others at a speed of 18 rpm. The two BPF are at 0.68 Hz (BPF2) and 0.88 Hz (BPF3). A peak indoor level of 58 dB at the first harmonic of BPF 3 (1.7 Hz) was measured

In any event, the Morgan residence data demonstrate that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away.

Data from Don Bonfiglio's Residence

As with the other Kumeyaay Wind-area study sites, the measurement data for Don Bonfiglio's residence, shown in Figure C- 9, display sound level peaks at the blade passage frequency of the nearest wind turbine (0.61 Hz) and the first three associated harmonics (1.2, 1.8 and 2.4 Hz). The sound levels, both indoors and outdoors, at these frequencies are in the range of 30 to 42 dB. The maximum inside level is 42 dB at 1.2 Hz (the frequency of the first harmonic of the blade passage frequency – BPF2).

While the coherence between the indoor and outdoor measurements is less than 0.5 at the blade passage frequency and associated harmonics, it is not surprising given the distance to the nearest wind turbine (2.9 miles, which is a greater distance than at any other Kumeyaay Wind-area study site except the Tisdale residence). Propagation effects (e.g., intervening terrain, atmospheric conditions) and interactions between infrasound from different wind turbines result in a more complex sound field at infrasound frequency as the distance increases. The wavelength of sound at 1 Hz is approximately 1,100 feet. At 2.9 miles the site is approximately 14 wavelengths from the sources of infrasound. Hence it is normal to witness declining coherence with increased distance due to this complexity. Also evident in the spectral data is a BPF peak at 0.39 Hz, which is most likely infrasound from Ocotillo Wind. There is also a harmonic at 0.78 Hz associated with the BPF.

Data from Donna Tisdale's Residence

The farthest (from a Kumeyaay Wind turbine) measurements we took were at the residence of Donna Tisdale, which is 5.7 miles from the nearest wind turbine. Yet even at that great distance, the data show as indicated in Figure C-10 peaks at the blade passage frequency (BPF2) of the nearest turbine (0.7 Hz) at Kumeyaay and its associated harmonics, albeit at lower sound pressure levels than observed at the closer study sites. The maximum measured indoor ILFN sound level was 43 dB at 0.7 Hz (the blade passage frequency). There is also a lower BPF at 0.39 Hz, which is most likely infrasound from Ocotillo Wind.

As similarly observed at the Bonfiglio residence, the coherence between the indoor and outdoor measurements at the Tisdale residence is mostly less than 0.5 for frequencies below 10 Hz. As indicated above, given the distance from the Tisdale residence to the nearest wind turbine (5.6 miles), this is not surprising. The Tisdale ranch is approximately 27 wavelengths from the wind turbines. The turbines are not visible from the ranch, because of intervening terrain. However the turbines are visible from some higher elevations of the ranch property.

Data from the Reference Sites

In contrast to the data for the Kumeyaay Wind-area residential measurement sites, the frequency and sound level data we present in the autospectra in Figures C-11 and C-12 for the two reference locations shows the autospectra values rather than the coherent output power. Because there was no option for making indoor sound measurements near the reference locations, we only used a single microphone to take measurements and thus did not measure a coherence or coherent output power. At both reference locations (K-R1 and K-R2), the data show clear sound level peaks at the blade passage frequency of the nearest turbine and the associated harmonics in the 0 to 5 Hz range. At K-R1, the sound levels of the peaks ranged from 53 dB to 60 dB (at the blade passage frequency, 0.84 Hz). At K-R2, which at 930 feet away was the measurement site closest to the Kumeyaay Wind turbines, the sound levels were even greater, between 60 dB and 70 dB for the spectral peaks below 3 Hz.

Tabulated Data

Table 6 lists the Kumeyaay Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels.

Table 6 Summary of Wind Turbine Noise for Kumeyaay Inside Residences

Residence	Distance[1]	Highest Sound Pressure Spectrum Level Indoors[2,3,4]	Frequency (Hz) of Peak Spectrum Level	Rotor Rotational Component
D. Elliott	2,960 feet	59 dB	1.6	1st harmonic
G. Thompson	2,880 feet	60 dB	0.8	BPF
R. Elliott	4,330 feet	53 dB	1.6	1st harmonic
K-LOSR	1.1 miles	48 dB	2.4	2nd harmonic
K. Oppenheimer	1.6 miles	51 dB	0.9	BPF
M. Morgan	1.7 miles	58 dB	1.7	1st harmonic
D. Bonfiglio	2.9 miles	42 dB	1.1	1st harmonic
D. Tisdale	5.7 miles	43 dB	1.4	1st harmonic

[1] Distance from closest wind turbine

[2] Decibels (re: 20 μPa)

[3] All but Live Oak Spring Resort, D. Elliott and G. Thompson data are coherent output power levels

[4] Oppenheimer data are estimated from coherent output power and correction for coherence

We note that while the Morgan residence data appears anomalous when compared with the trend of sound pressure levels as a function of distance from the wind turbines, it is not. Instead, the Morgan residence data demonstrates that under the right weather and topographical conditions, large wind turbines like those used at Kumeyaay Wind can produce high levels of ILFN inside buildings even miles away. It appears that one factor that contributed to the higher infrasound levels at the Morgan residence is the fact that this house was located downwind of multiple turbines, whereas the other residences except for Mr. Elliott's were either upwind of the turbines and/or had a more obscured line-of-sight to the full array of turbines compared to the Morgan's.

Noise Data for Ocotillo Wind

The noise spectra for the Ocotillo Wind-area measurements are displayed in Figures C-13 through C-21 in Appendix C. Table 7, below, summarizes much of the relevant data for the residential measurements.

In contrast to the relatively consistent wind conditions in the Kumeyaay Wind area throughout the measurement periods, the wind at the Ocotillo Wind Energy Facility varied greatly across the measurement periods. During the first recordings on the morning of April 29, the wind was generally light and the turbine blades were rotating slowly (less than 10 rpm). In the afternoon, however, the wind picked up considerably and the rotational speed of the turbine blades increased (e.g. 13 rpm). And later that night, when we took our last measurements, the wind speed had increased even more, causing the turbine blades to rotate even faster (i.e., 16 rpm observed at 7:51 pm just before dark). Between the first measurements in the morning and the last measurements at night, the turbines' average blade passage frequency increased from 0.5 Hz to 0.8 Hz.

The Ocotillo recordings were analyzed several different ways using cross-correlation, longer averaging times and 1/3-octave band filtering among other methods, without significantly changing the results. For the Ocotillo data, the coherence between the indoor and outdoor signals is low (i.e., less than 0.5). This, along with the spectral data, indicates a complex sound field with more than one BPF present, rather than a classical spectrum of tonal components including just one BPF and its harmonics. Note that it was only possible to observe a handful of turbines at a time out of the 112 turbines at Ocotillo Wind. Consequently, the BPF indicated in Table 5 for the Ocotillo recordings represent the BPF of the turbine or turbines closest to the reference location measurements and not the BPF for turbines in the entire facility.[26]

One possible explanation for low coherence is that Ocotillo Wind has so many turbines spread out over such a large area (with accompanying differences in wind speed and direction at each turbine), the ILFN produced by the turbines at Ocotillo has a greater probability of being less strongly synchronized as it is at Kumeyaay, for example, where the turbines are arrayed in a line on a ridge and experience a much more uniform wind configuration (i.e., speed and direction). At Ocotillo, it is much more likely that the wind turbines rotate at different speeds from one another. Thus where a residence or other receptor is exposed to ILFN from more than one

[26] After dark (approximately 8 pm) on 30 April 2013 it was not possible to observe the rotational speed of turbines at Ocotillo Wind. However, it was possible to deduce the rotational speed of the turbines from the measured data.

turbine, which will usually be the case with most Ocotillo-area locations, it will experience a complex sound field with varying tonal components derived not only from the different turbines directly, but also possibly from the interaction of tonal components from a multitude of turbines.

Another possible factor contributing to the lower coherence between outdoor and indoor sound levels at Ocotillo could be that the residential structures alter the frequency of the WT noise just enough as the sound energy passes through them that the sound indoors is at a slightly different frequency than the sound outdoors. Although this effect is not as apparent in the Kumeyaay data, it is possible that the distributed pattern of the Ocotillo wind turbines makes it more apparent here.

Data for the Residential Sites

As evidenced by the data in Table 7 and by comparing the coherent output power spectra from the morning and night measurements at the Pelley residence (Figures C-13 and C-14), as well as the afternoon and night measurements at the Ewing residence (Figures C-15 and C-16), the ILFN sounds pressure level increased substantially as the wind speed picked up and the blade passage frequency of the turbines increased. This indicates not only that the Ocotillo Wind turbines produced much of the measured ILFN, but that the turbines can create very high ILFN sounds levels even at substantial distance. The Tucker residence data are shown in Figures C-17 and C-18.

Looking specifically at the Pelly residence data for the daytime measurement (Figure C-14) it would appear that there are two blade passage frequencies present (0.5 and 0.6 Hz). This is not surprising considering the distribution of turbines over a large area where different turbines see different wind conditions. The spectral peaks above the blade passage frequencies are consistent with this assessment. The two blade passage frequencies indicate corresponding rotational speeds of 10 and 12 rpm.

Two distinct blade passage frequencies (0.68 and 0.88 Hz) are also evident from the nighttime measurements at the Pelley residence. These blade passage frequencies are indicative of rotation speeds of 13.6 and 17.6 rpm respectively. Although the higher rotational speed is slightly above the reported, operational speed range (6 to 16 rpm) for the Siemens turbines, there is no other source for the infrasound in this area. Note that the outdoor coherent output power spectrum is omitted for clarity in Figure C-14.

The spectra from the Ewing residence likewise indicate two different blade passage frequencies during both the day and night. In Figure C-15 we see the same frequency of the second BPF of 0.88 Hz in the daytime data, confirming that in fact this is infrasound from the Ocotillo WTs. The nighttime data at the Ewing residence as shown in Figure C-16 indicates two BPF also (0.39 and 0.49 Hz) and their associated harmonics.

The data for the Tucker residence similarly contain two BPF during the day (0.6 and 0.8 Hz) and two in the nighttime (0.39 and 0.68 Hz), with the lower BPF reflected in the data at the Ewing residence at night.

Whereas the Pelly residence data indicates an amplification of sound level between inside and outside, the data for other two residences indicate the opposite. Apparently the Ewing residence is more tightly sealed. It also seemed to be of a more substantial construction. The Tucker residence data also shows a reduction from outside to inside. An explanation for this effect could be the shielding provided by neighboring structures, which are more closely spaced than at the Pelly residence. The Tucker residence may also be more tightly sealed.

That the Ocotillo Wind turbines generated much of the ILFN measured at the Pelley and Ewing residences is strongly supported by the fact that the recorded data for both residences show sound level peaks at the turbine blade passage frequencies and many of the associated harmonics. The reference location measurement data also demonstrate this pattern, although not as clearly.

Data for the Reference Sites

At reference location 1 for the Ocotillo Wind-area measurements (O-R1), the nighttime ILFN levels were quite high, with multiple peaks above 60 dB including at frequencies that correspond to many of the harmonics of the blade passage frequency of the nearest wind turbine. The overall peak sound level of 74 dB occurred at the blade passage frequency (0.8 Hz). At O-R2, which at 1,470 feet away was the measurement site closest to the Ocotillo Wind turbines, the peak sound level of 78 dB was even greater, and also occurred at the blade passage frequency of 0.8 Hz. Similarly, at O-R3, which was adjacent to the Ocotillo substation, the peak sound level was 77 dB and occurred at the blade passage frequency of 0.8 Hz. These data are shown in Figures C-19 through C-21.

Tabulated Data

Table 7 lists the Ocotillo Wind-area residential measurement locations, along with their distance from the nearest wind turbine, the highest measured indoor sound pressure levels, and the frequency of those peak sound pressure levels. As expected given higher wind speeds at night, nighttime, indoor noise levels range from 15 to 27 dB higher than those measured during the day.

Table 7 Summary of Wind Turbine Noise for Ocotillo Inside Residences

Residence	Distance[1]	Time of Day	Highest Sound Pressure Spectrum Level Indoors[2,3]	Frequency (Hz) of Spectrum Peak Level	Rotor Rotational Component
Pelley	3,220 feet	Day	42 dB	0.6	BPF2
			49 dB	1.0	1st of BPF1
		Night	67 dB	0.68	BPF1
			69 dB	0.88	BPF2
Ewing	3,590 feet	Day	48 dB	0.59	BPF1
			51 dB	0.88	BPF2
		Night	42 dB	0.39	BPF1

			59 dB	0.78	1st of BPF2
Tucker	1.2 miles	Day	42 dB	0.6	BPF1
			48 dB	0.8	BPF2
		Night	66 dB	0.68	BPF2
			69 dB	1.37	1st of BPF2

[1] Distance from closest wind turbine

[2] Decibels (re: 20 μPa)

[3] All are coherent output power spectrum levels

DISCUSSION OF RESULTS

It is clear from the measured noise data obtained from Kumeyaay and Ocotillo facilities that there is significant wind turbine-generated ILFN. This was to be expected as it has been documented by others such as in the McPherson noise study, the Shirley Wind Turbine study, and by Epsilon Associates.[27] And indeed the measured ILFN levels near Kumeyaay and Ocotillo wind turbine facilities are similar to those measured in previous studies after accounting for the proximity of the measurements to a wind turbine and the total number of the wind turbines in the facility.

Both the McPherson and Shirley wind turbine noise studies were conducted to investigate whether and at what levels the subject wind turbines (the turbines in Falmouth, Massachusetts, and those in the Shirley Wind Project in Brown County, Wisconsin) produce ILFN, and whether that ILFN was contributing to the significant health and other impacts reported by nearby residences. In some cases, the impacts were so severe that residents abandoned their homes. Both studies found high levels of wind turbine-generated ILFN at numerous nearby residences that correlated with residents' reported impacts.

Human health impacts from wind turbines had been reported previously in several countries with large wind facilities in proximity to residences. But these impacts were often attributed to certain individuals' aversion to the presence of a large industrial facility constructed in what was previously a quiet rural setting. Scientific understanding has developed significantly since then.

Recent research and investigations into human response to ILFN have been conducted and seem to provide strong evidence of a cause and effect relationship. In particular the work of Salt, et al.[28] has made a clear case for perception of ILFN below the threshold of hearing as defined by ISO 389-7 which is related to the response of the ear's inner hair cells (IHC). Salt has demonstrated that it is possible for the ears' outer hair cells (OHC) to respond to ILFN at sound

[27] Epsilon Associates, A Study of Low Frequency and Infrasound from Wind Turbines, July 2009.

[28] Alec Salt, and J. Lichtenhan, Perception based protection from low-frequency sounds may not be enough, Internoise 2012, August 2012.

pressure levels that are much lower than the IHC threshold. Salt has reported that ILFN levels (levels commonly generated by wind turbines nearby residences) can cause physiologic changes in the ear.[29] Salt and Kaltenbach "estimated that sound levels of 60 dBG will stimulate the OHC of the human ear."[30]

Furthermore, Matsumoto et al.[31] have demonstrated in a laboratory setting that humans can perceive ILFN at sound pressure levels below the IHC threshold when the noise is a complex spectrum (i.e. contains multiple frequency components). From this laboratory research it was clearly demonstrated that humans can perceive sound pressure levels that are from 10 to 45 decibels (dB) less than the OHC threshold in the ILFN range. In fact, the Matsumoto thresholds clearly follow the OHC threshold down to the frequency below which the two diverge. The Matsumoto thresholds are lower than the OHC thresholds at frequencies below the point at which they diverge.

These studies and more recent studies demonstrate that wind turbines (specifically wind turbine-generated ILFN) have the potential to not only annoy humans, but harm them physiologically.

The data presented herein represent the conditions of measurement during the study and do not necessarily represent maximum noise conditions produced by the Kumeyaay and Ocotillo facilities. Higher wind speeds generally produce higher noise levels in particular higher ILFN. This is clearly demonstrated in the Ocotillo data when comparing the daytime and nighttime levels.

NOISE METRICS FOR MEASURING ILFN

There are several noise metrics which are used to quantify environmental noise levels. The most common metric is A-weighting (A-wt). The A-wt curve is shown in Figure 6. The A-wt metric is intended to approximate the loudness sensitive of the human ear for common environmental sounds in the range of 20 to 20,000 Hz. A-wt at 1 Hz is -149 dB. Hence a noise limit based on A-wt would not be appropriate to address ILFN, a major component of which is sound below 20 Hz.

A noise metric sometimes used when there is low frequency noise is the C-weighting (C-wt). While the C-wt metric does attempt to address low frequency noise better than A-wt, it would also not be appropriate for quantifying infrasound, since it still strongly de-emphasizes sound at frequencies below 20 Hz as shown in Figure 6. C-wt at 1 Hz is -52.5 dB.

One noise metric recently used to quantify ILFN is G-weighting (G-wt). The G-wt measure has been used in Europe. G-wt would certainly be a more representative measure of ILFN than

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[29] Alec Salt, and J.A. Kaltenbach, "Infrasound from Wind Turbines Could Affect Humans," Bulletin of Science, Technology and Society, 31(4), pp.296-302, September 12, 2011.

[30] Ibid., p. 300, "As discussed below, G-weighting (with values expressed in dBG) is one metric that is used to quantify environmental noise levels. While it is a more accurate measure of ILFN than most other metrics, G-weighting still de-emphasizes infrasound."

[31] Yasunao Matsumoto, et al, An investigation of the perception thresholds of band-limited low frequency noises; influence of bandwith, published in The Effects of Low-Frequency Noise and Vibration on People, Multi-Science Publishing Co. Ltd.

either the A- wt or the C- wt metrics, but as shown in Figure 6 it too de-emphasizes the very low frequency infrasound by -40 dB at 1 Hz.

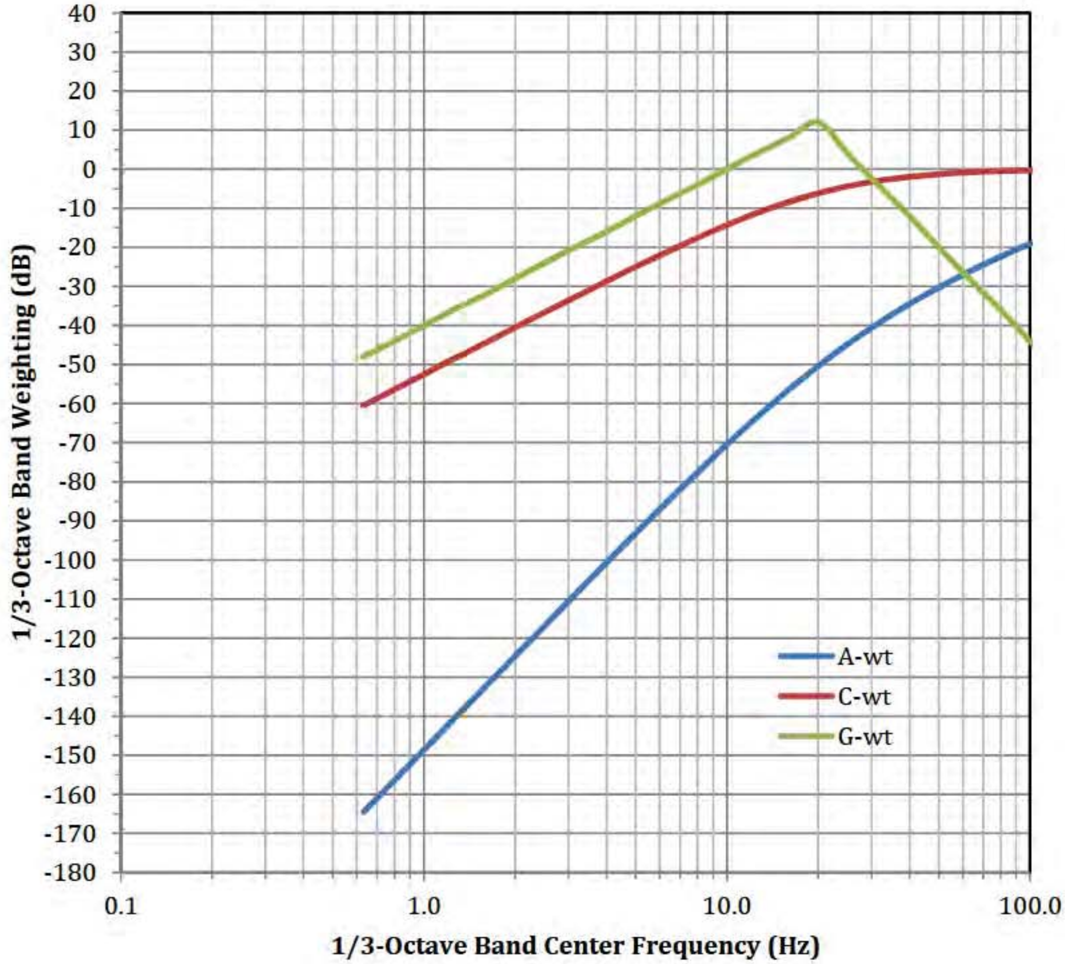


Figure 6 A, C and G Spectral Weighting Curves

CONCLUSION

The results of this study conclusively demonstrate that both the Kumeyaay and Ocotillo facilities' wind turbines generate ILFN at residential and other locations up to 15 miles away.

TERMINOLOGY

- Autospectrum: The autospectrum is the narrow band, energy average sound pressure level spectrum (in dB) measured for a specific time interval.
- Coherence: The spectral coherence is a statistic that can be used to examine the relation between two signals or data sets. It is commonly used to estimate the power transfer between input and output of a linear system. If the signals are ergodic, and the system function linear, it can be used to estimate the causality between the input and output.
- Cross-spectrum: In time series analysis, the cross-spectrum is used as part of a frequency domain analysis of the cross correlation or cross covariance between two time series.
- Cycles per second: A unit of frequency, same as hertz (Hz).
- Decibel (dB): A unit of level which denotes the ratio between two quantities that are proportional to power; the number of decibels is 10 times the logarithm (to the base 10) of this ratio. For sound, the reference sound pressure is 20 micro-Pascals.
- FFT (fast Fourier transform): An algorithm to compute the discrete Fourier transform and its inverse. A Fourier transform converts time to frequency and vice versa; an FFT rapidly computes such transformations.
- ILFN: Infrasound and low frequency noise.
- Infrasound: Sound at frequencies lower than 20 Hz.
- Low frequency noise: Noise at frequencies between 20 and 200 Hz.
- Noise level: The sound pressure energy measured in decibels.

APPENDIX A – MEASUREMENT LOCATIONS

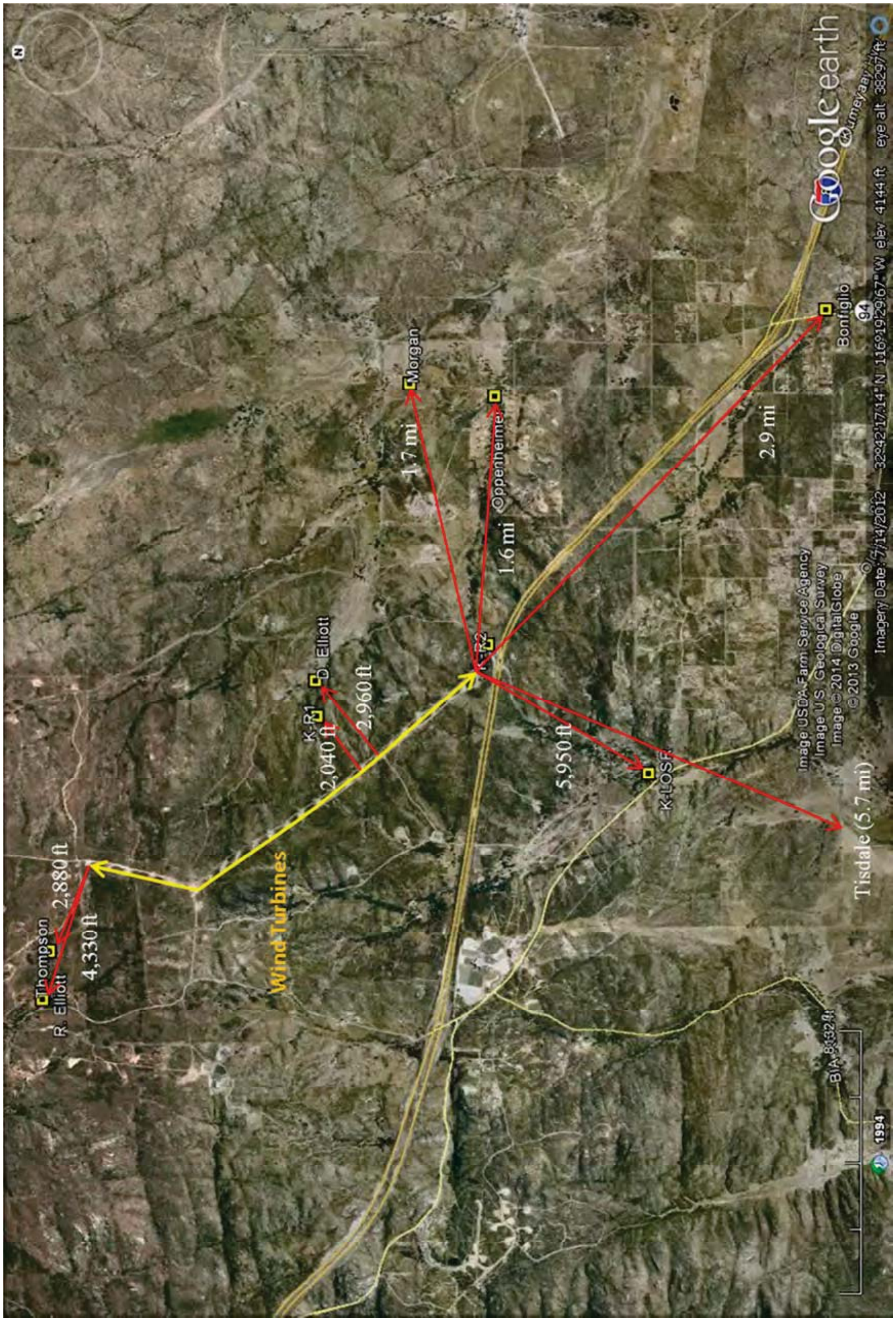


Figure A - 1 Kumeyaay Measurement Locations

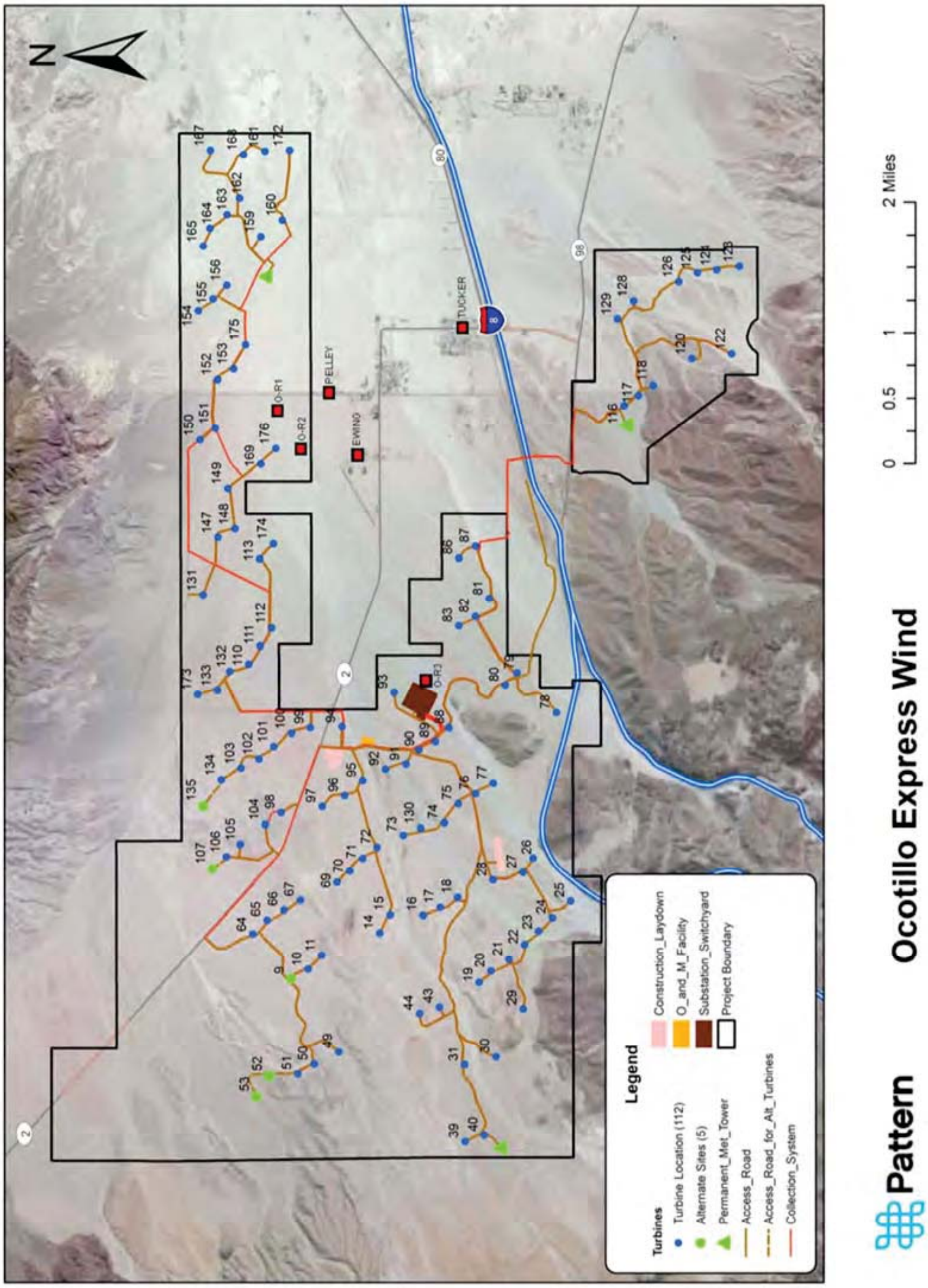


Figure A - 2 Ocotillo Measurement Locations

APPENDIX B – METEOROLOGICAL DATA

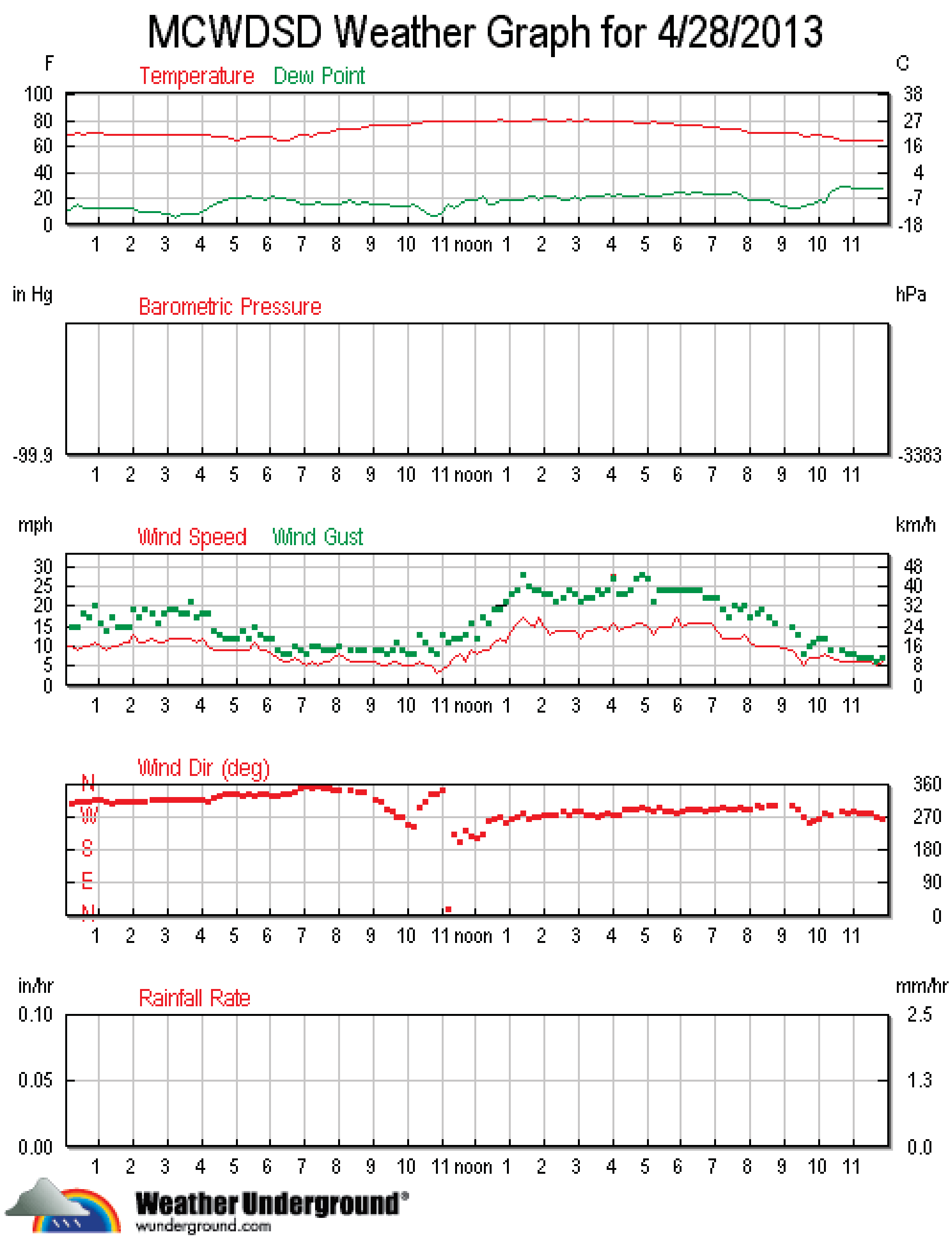


Figure B - 1 Weather Data for Kumeyaay 28 April 2013

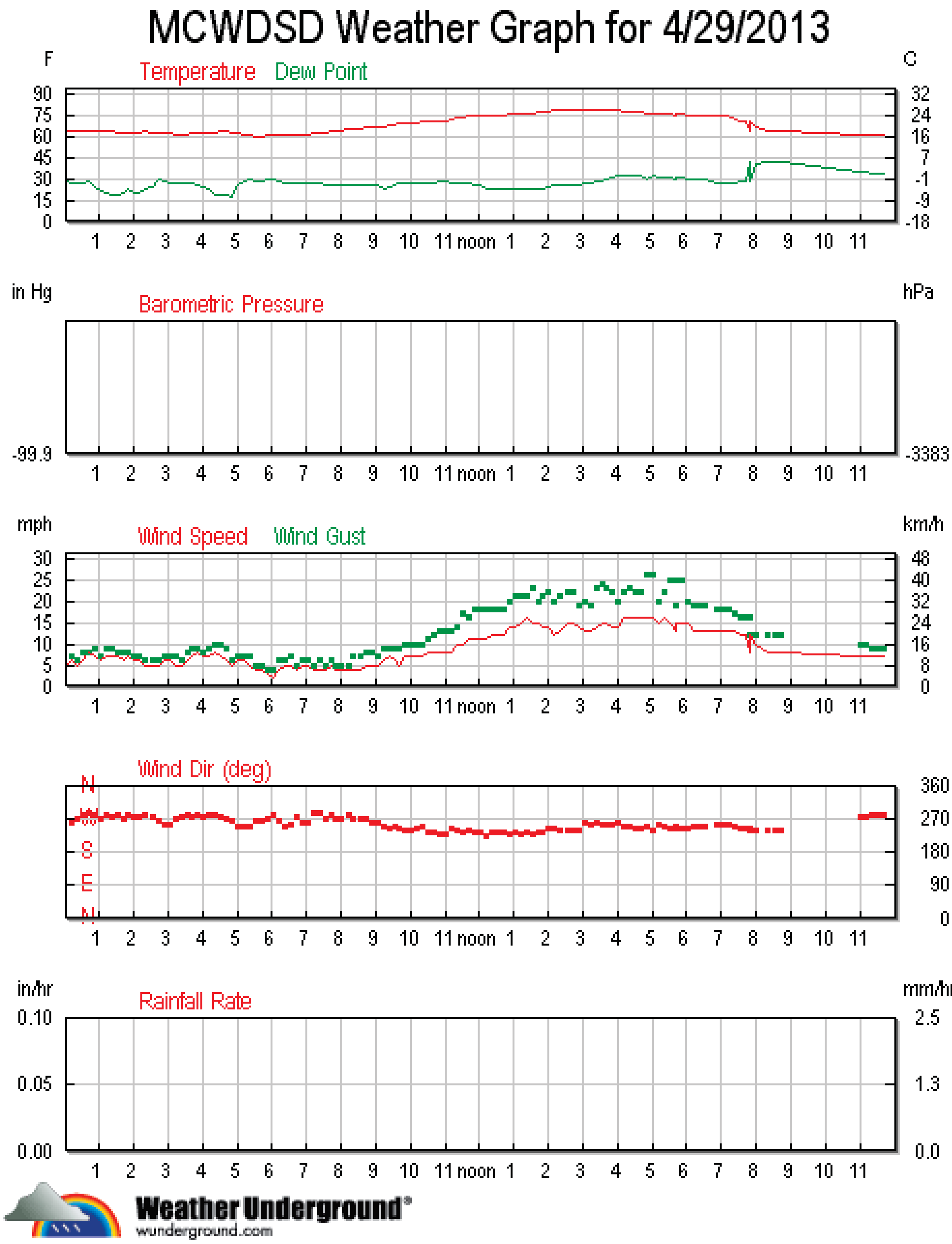
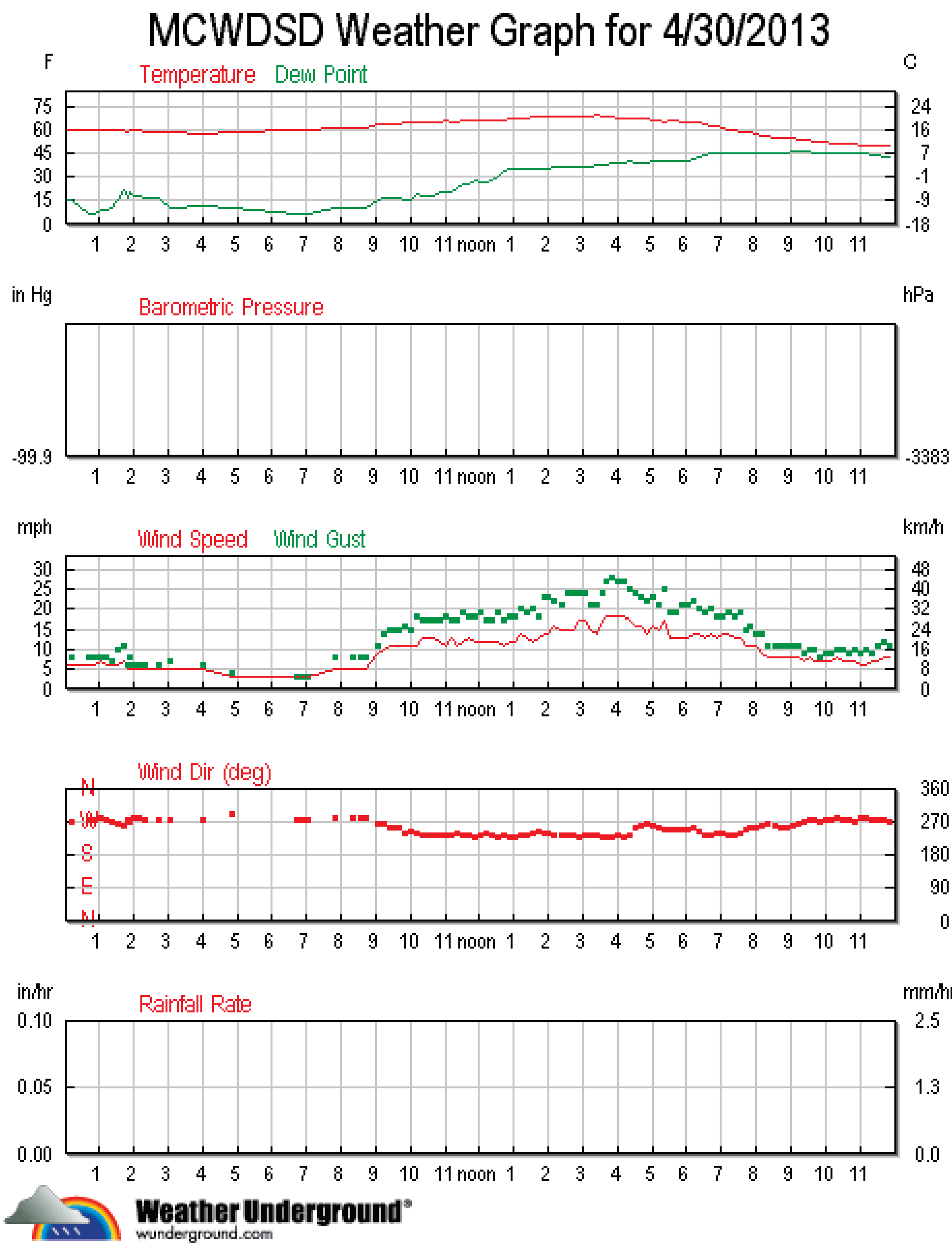


Figure B - 2 Weather Data for Kumeyaay April 29 2013



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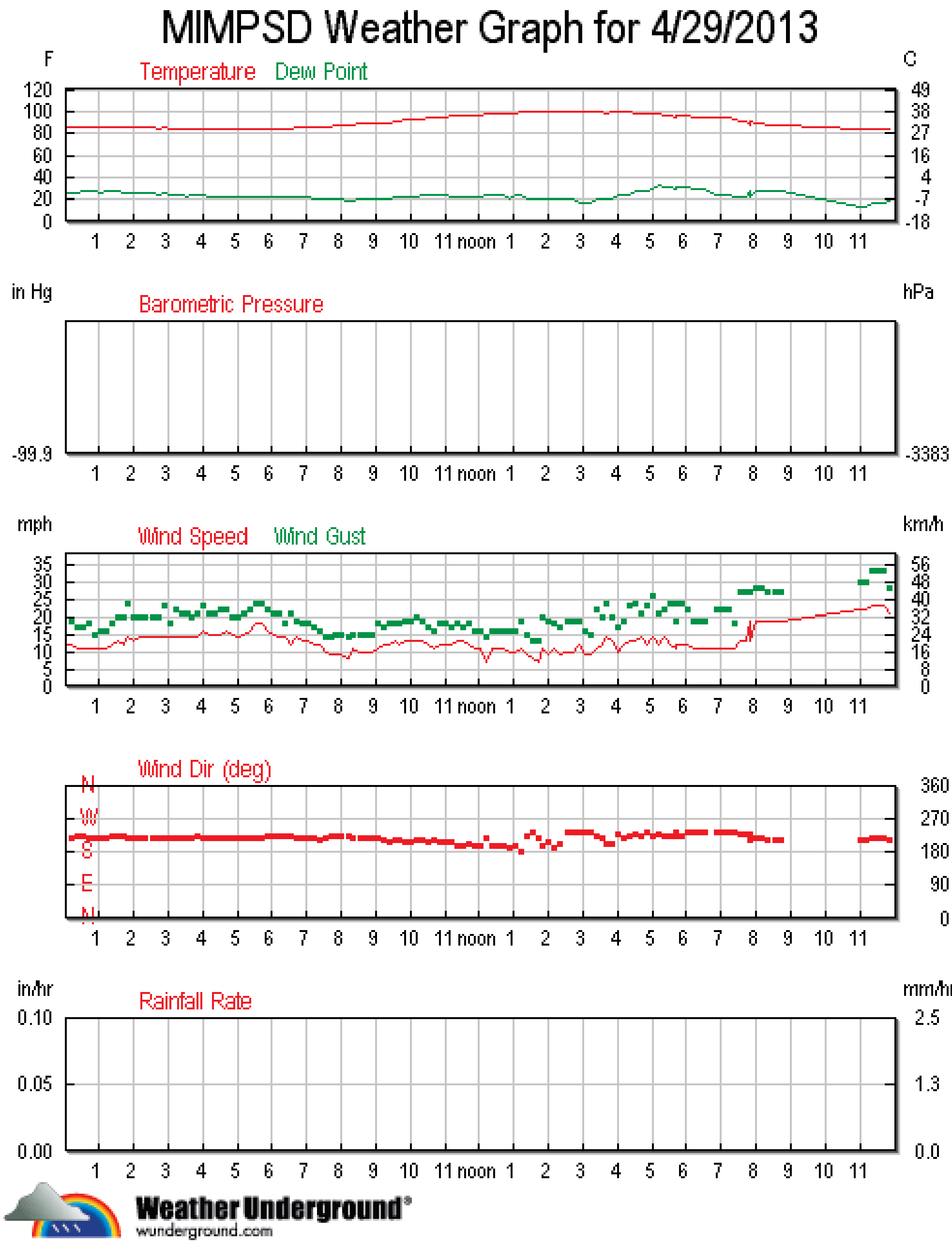

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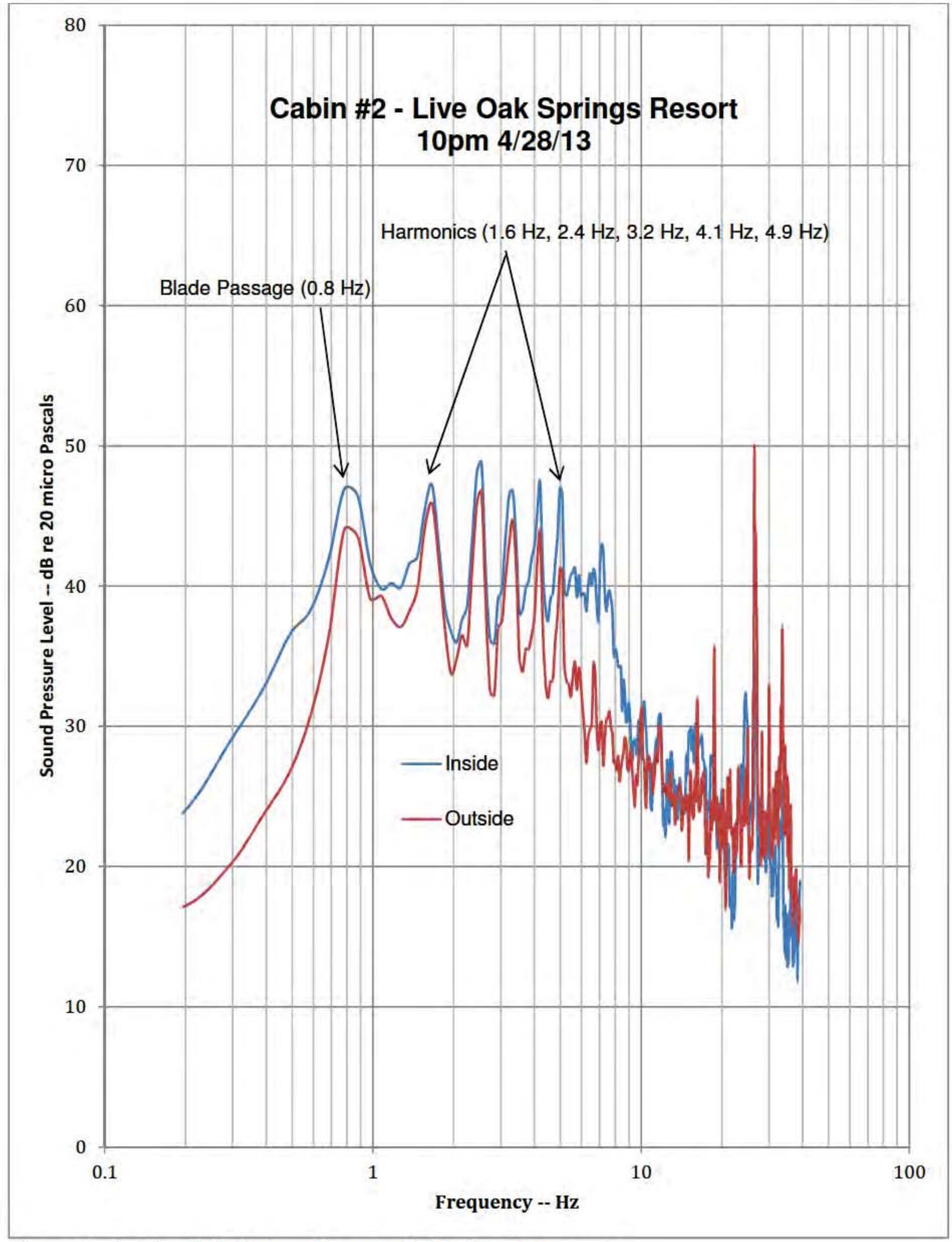

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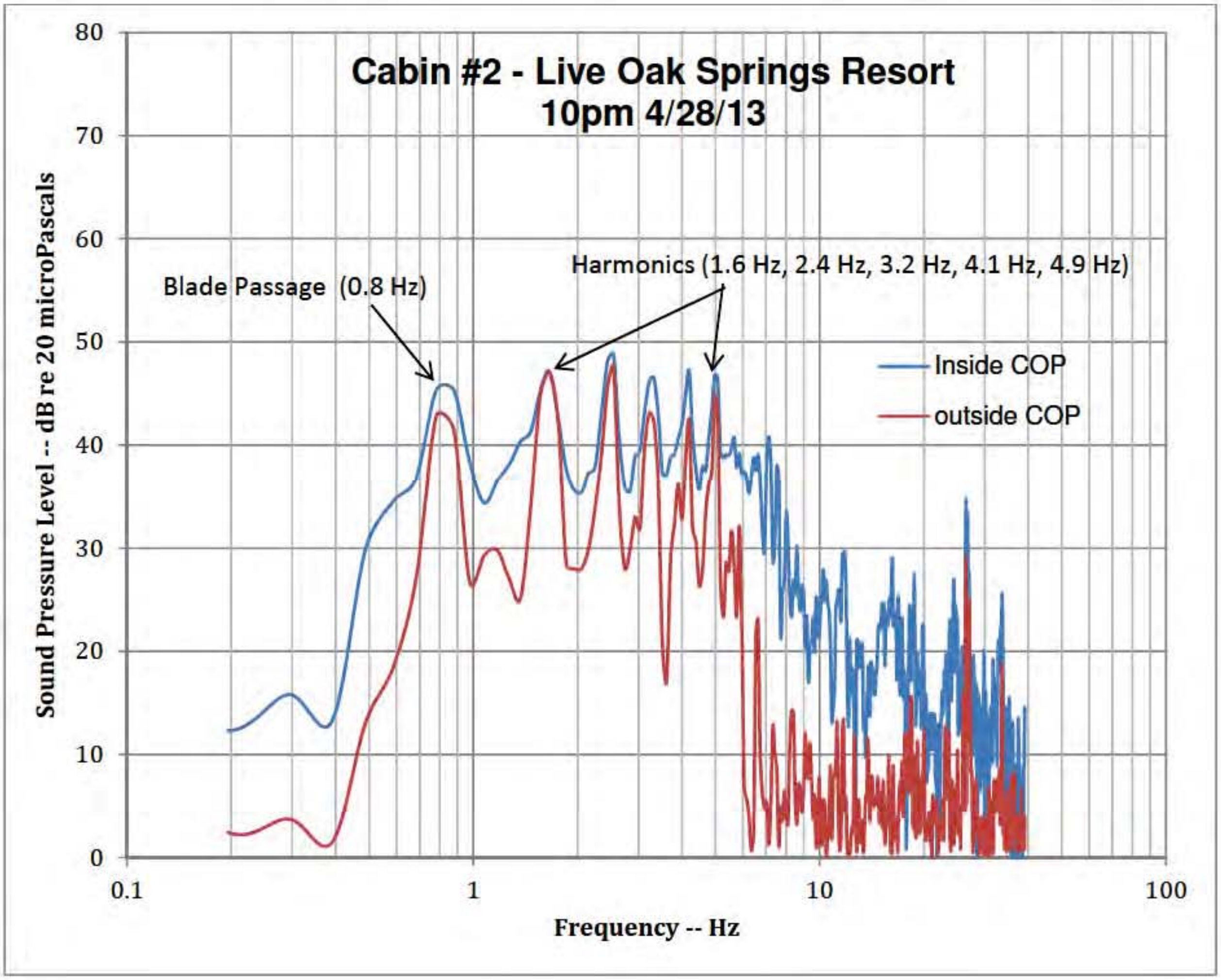

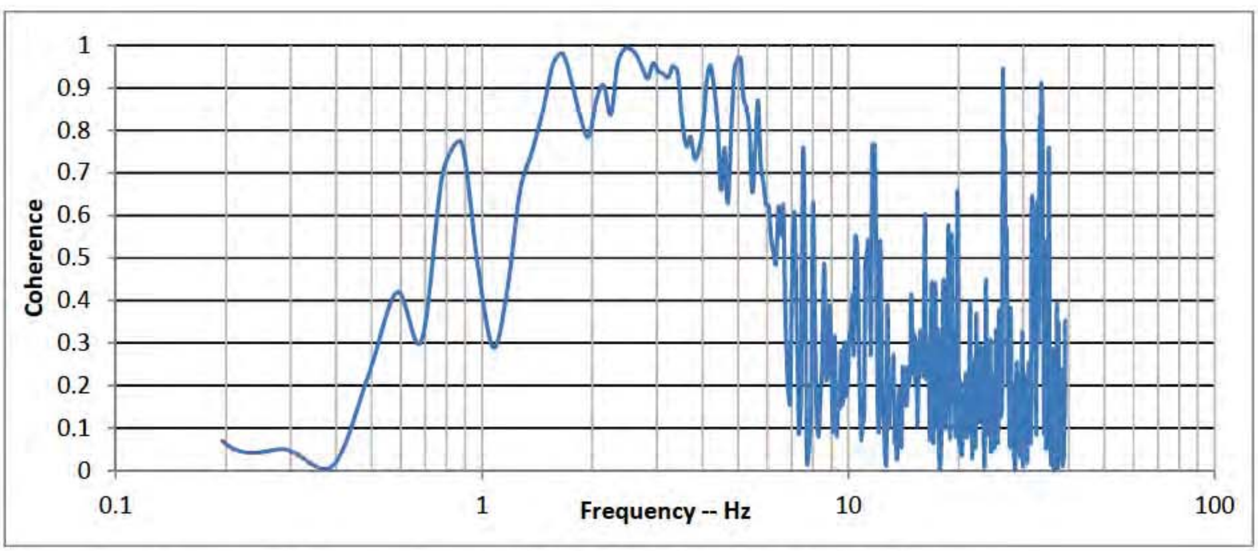

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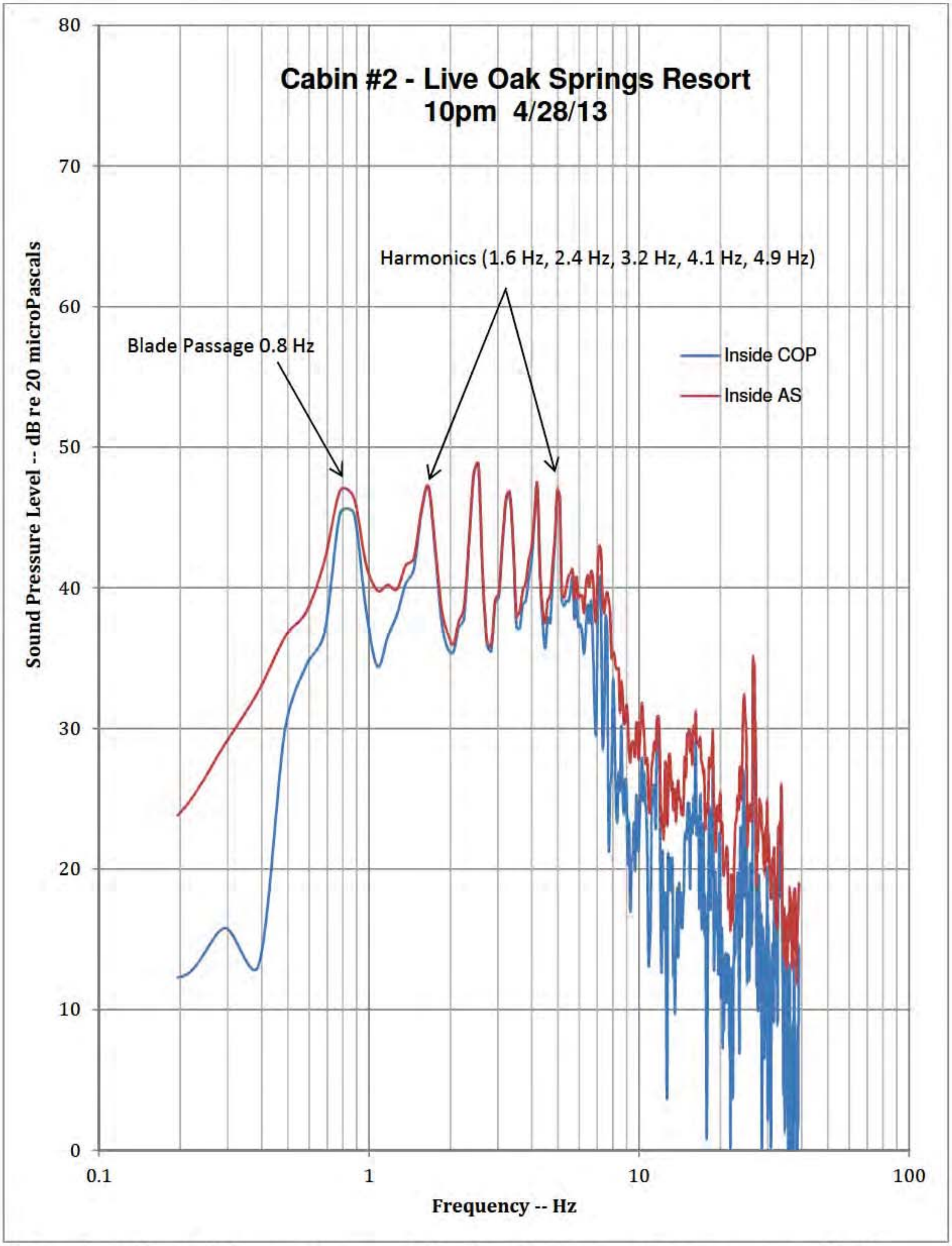

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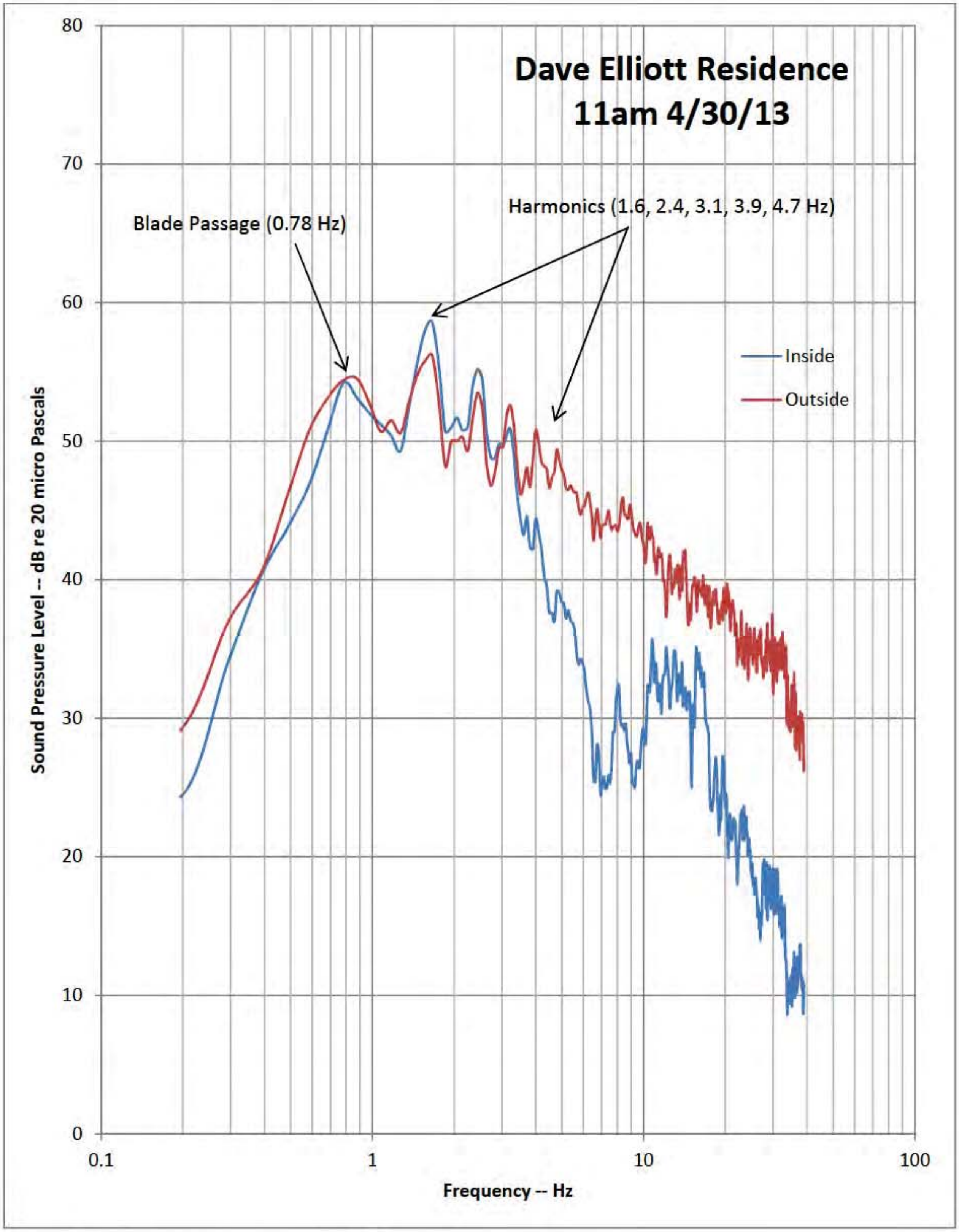

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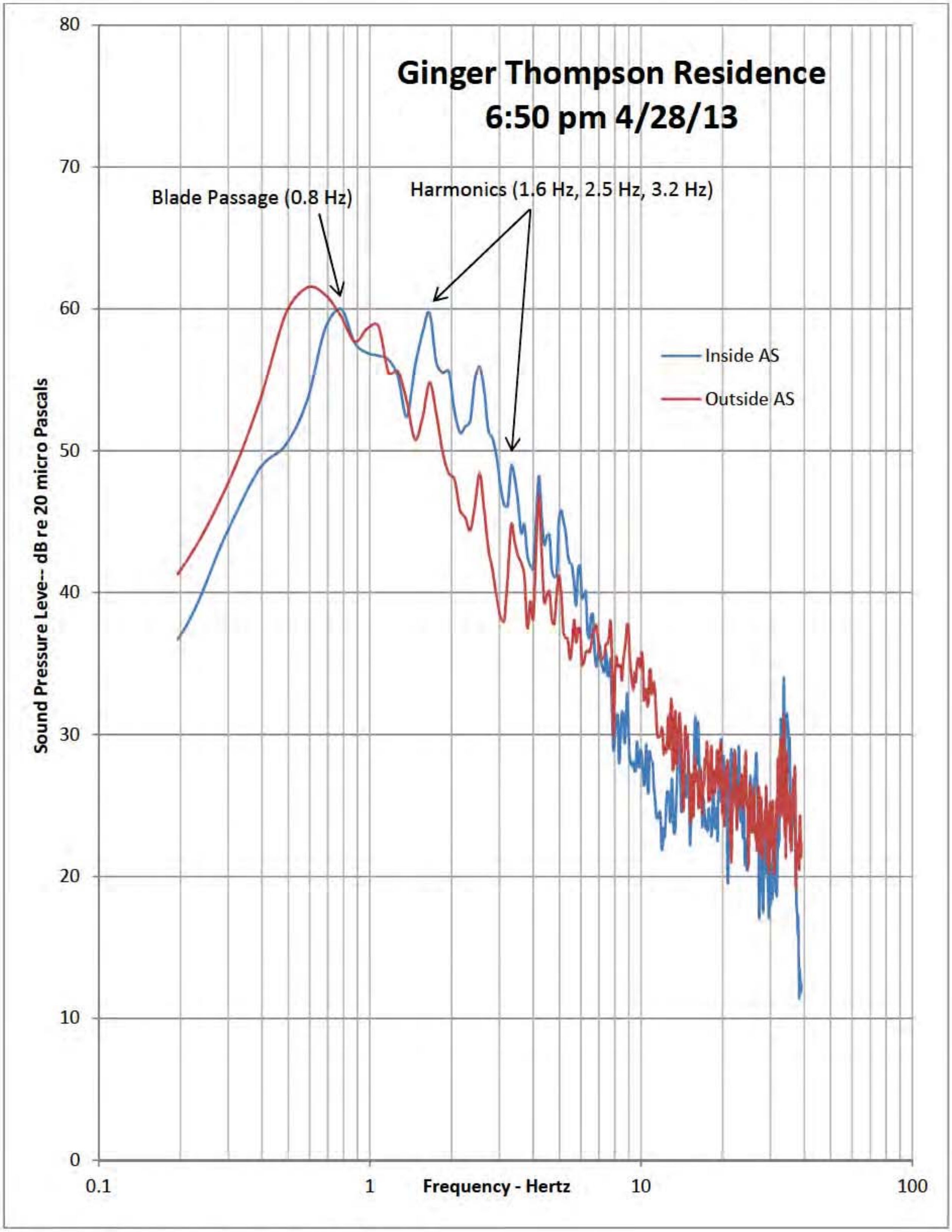

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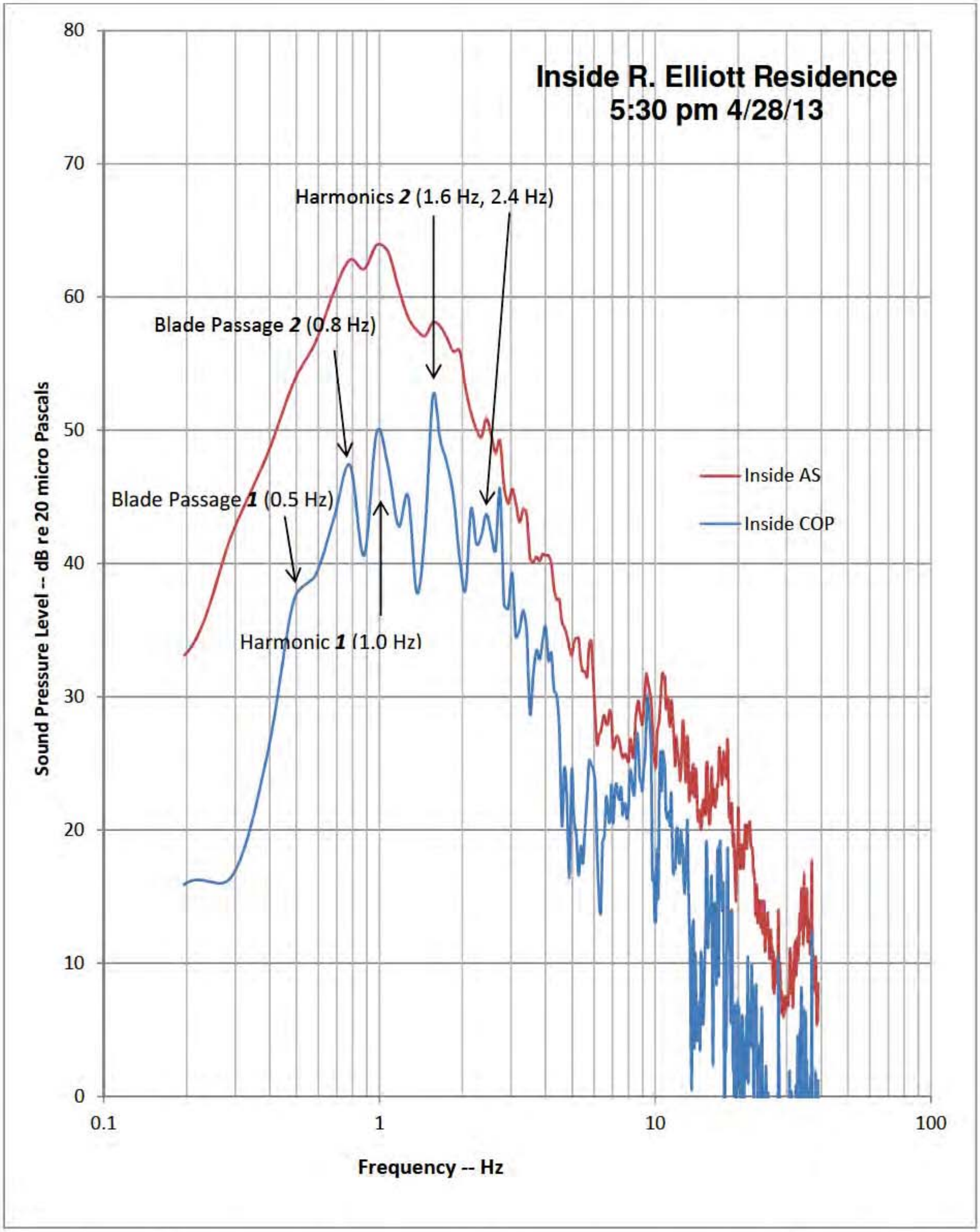

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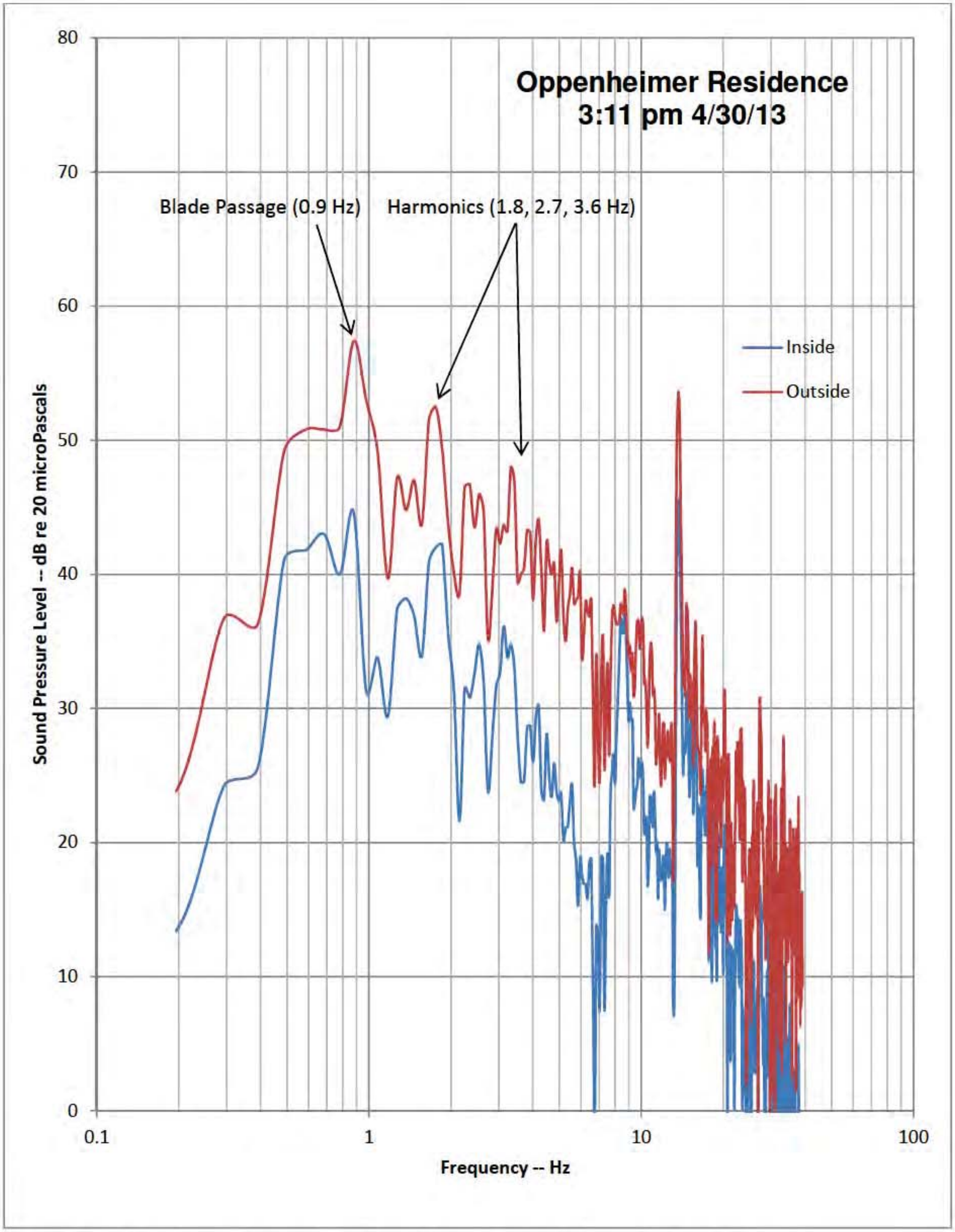

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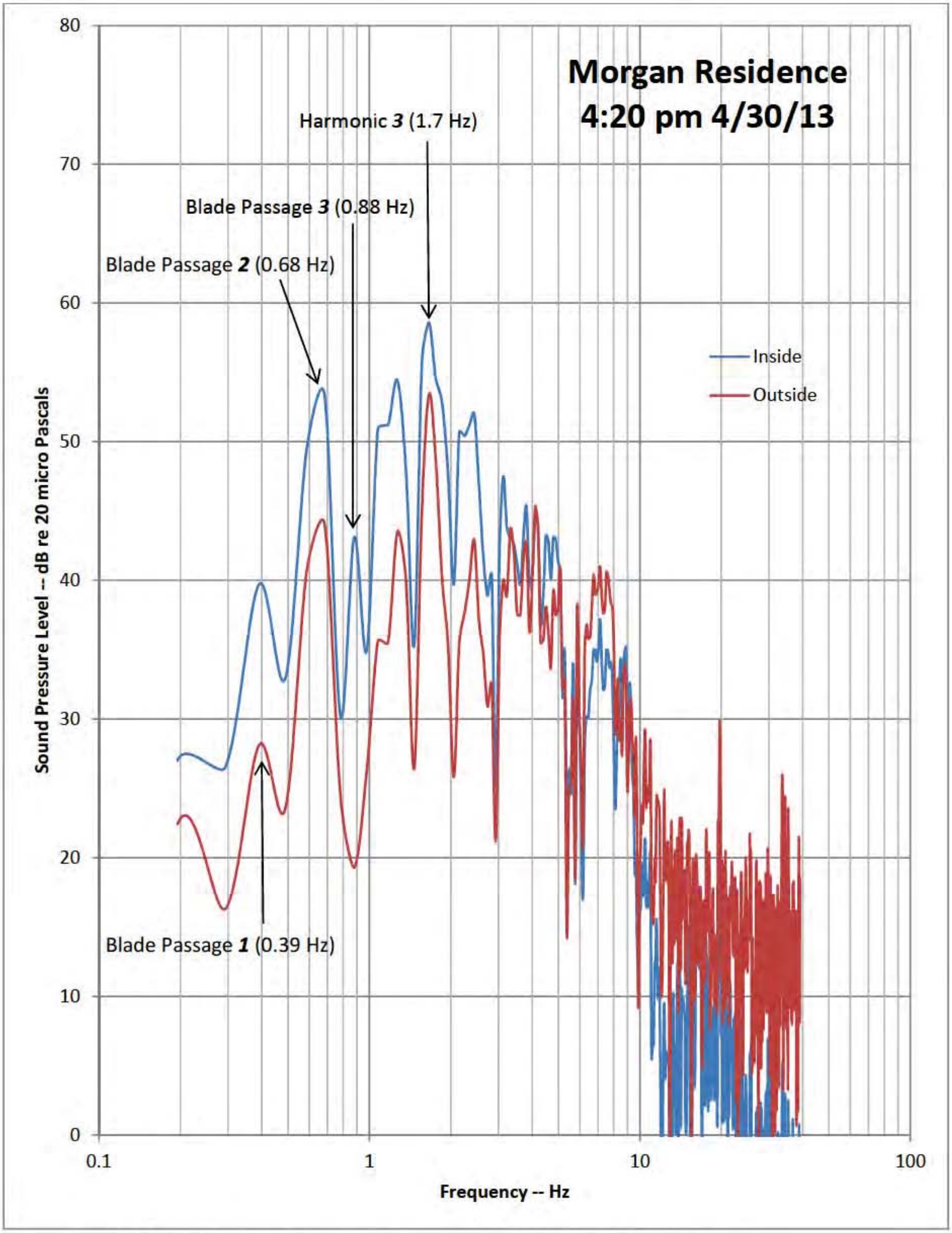

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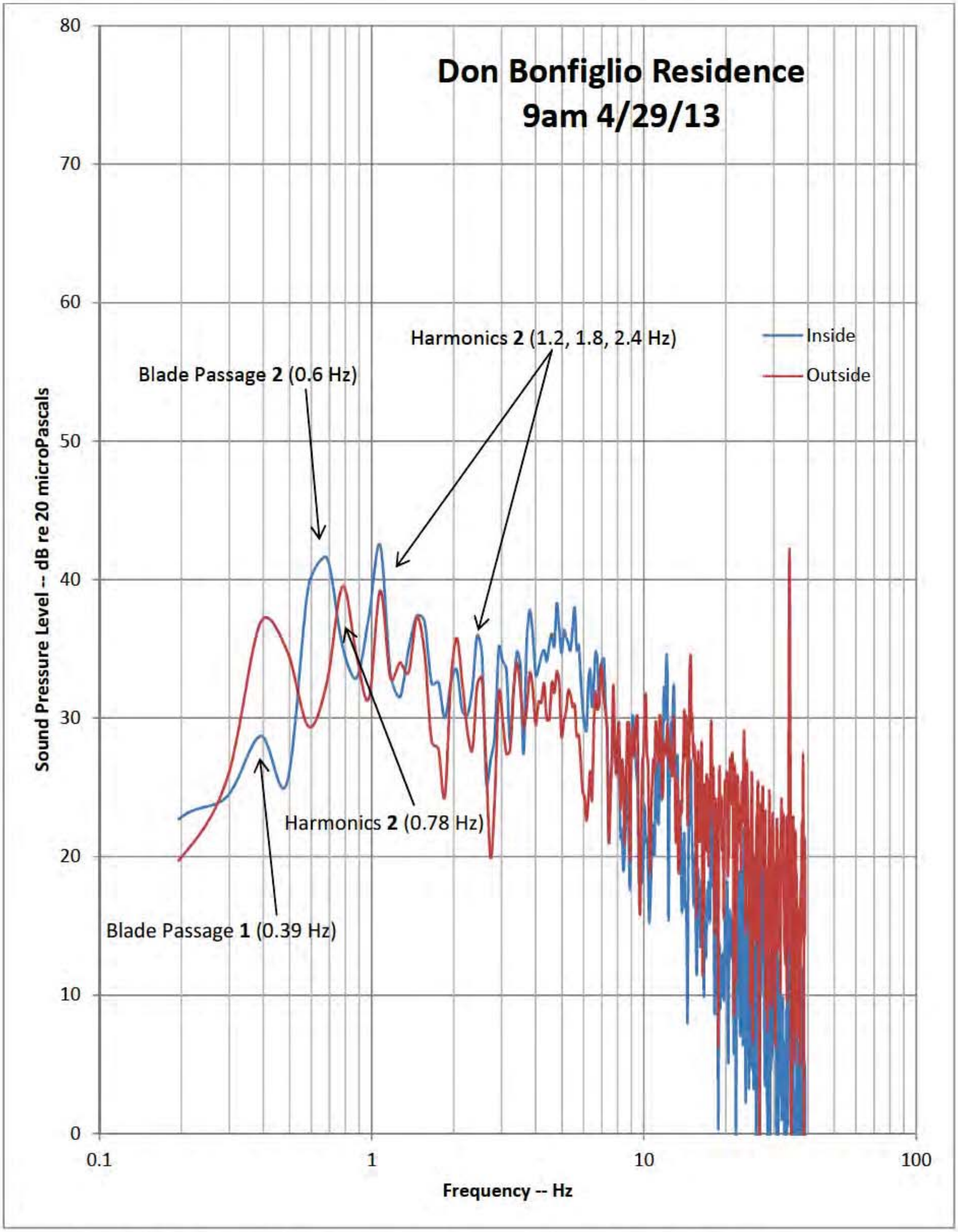

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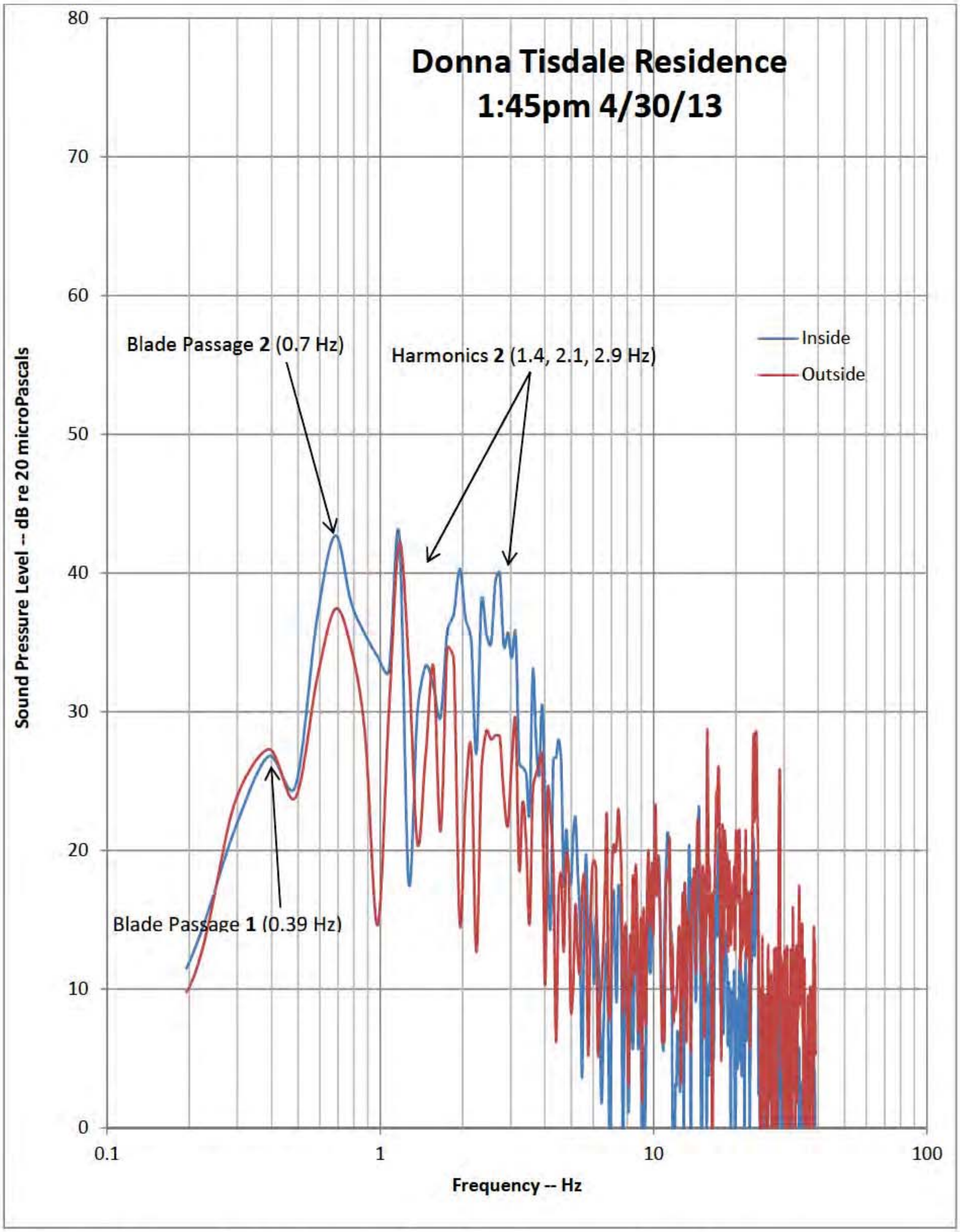

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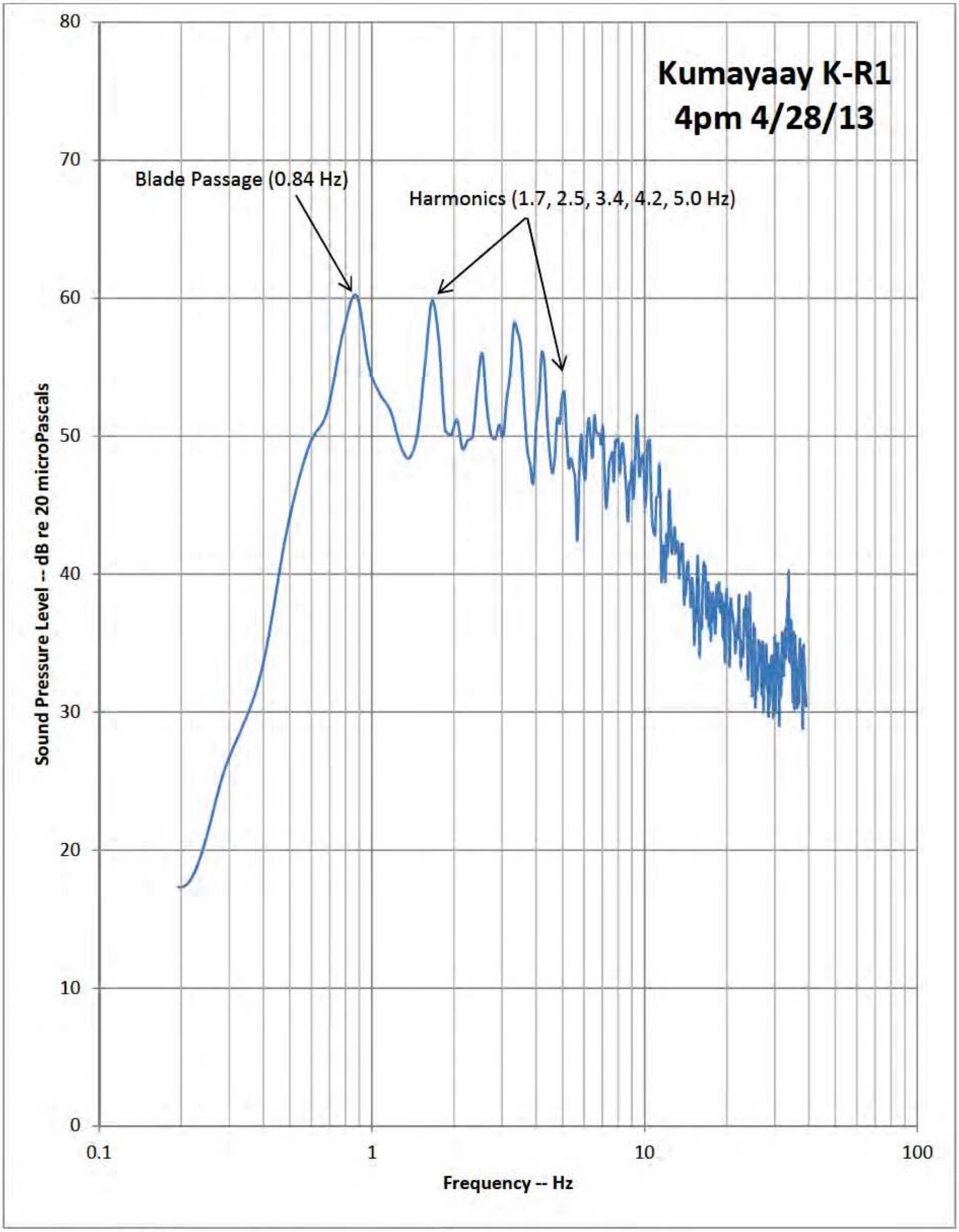

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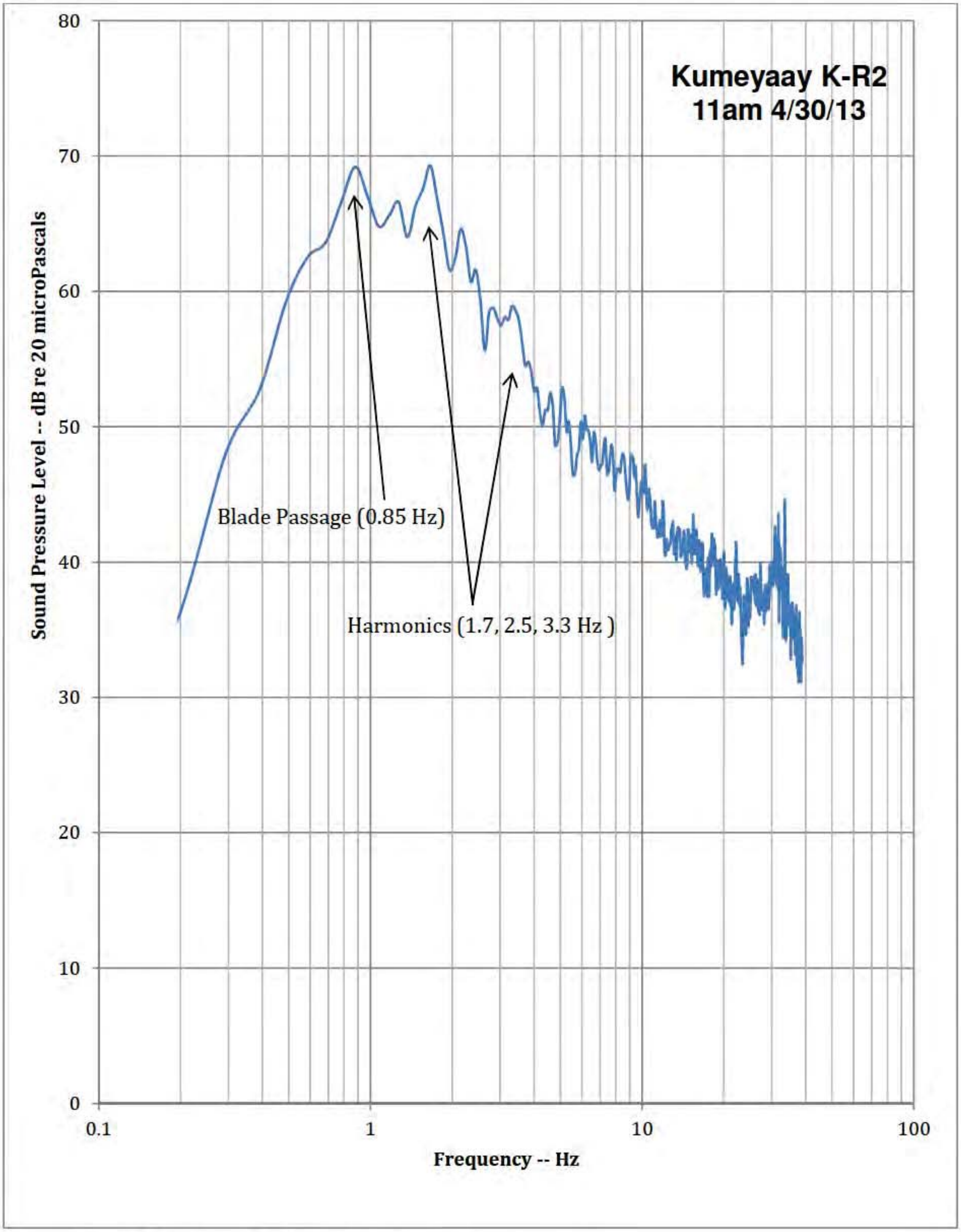

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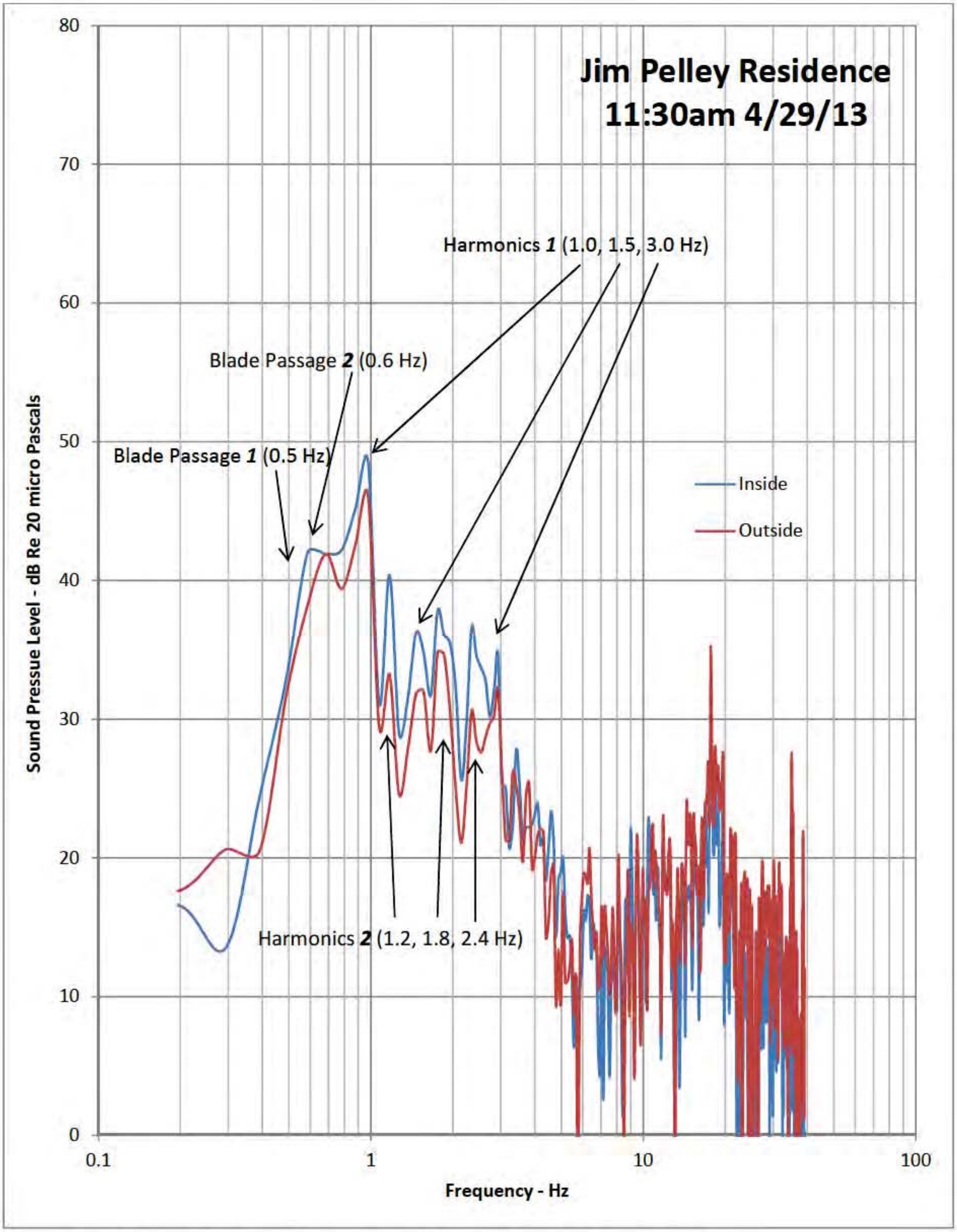

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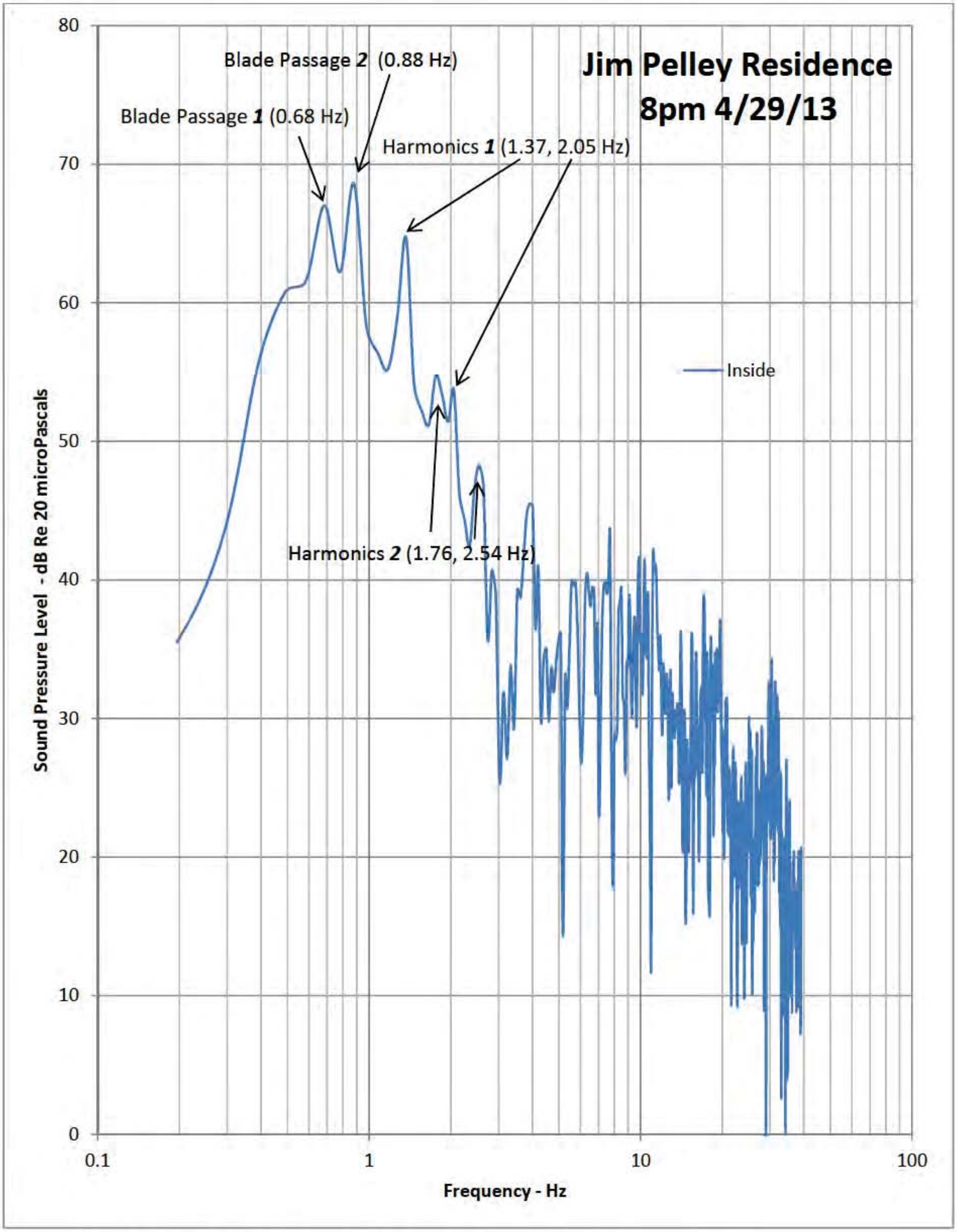

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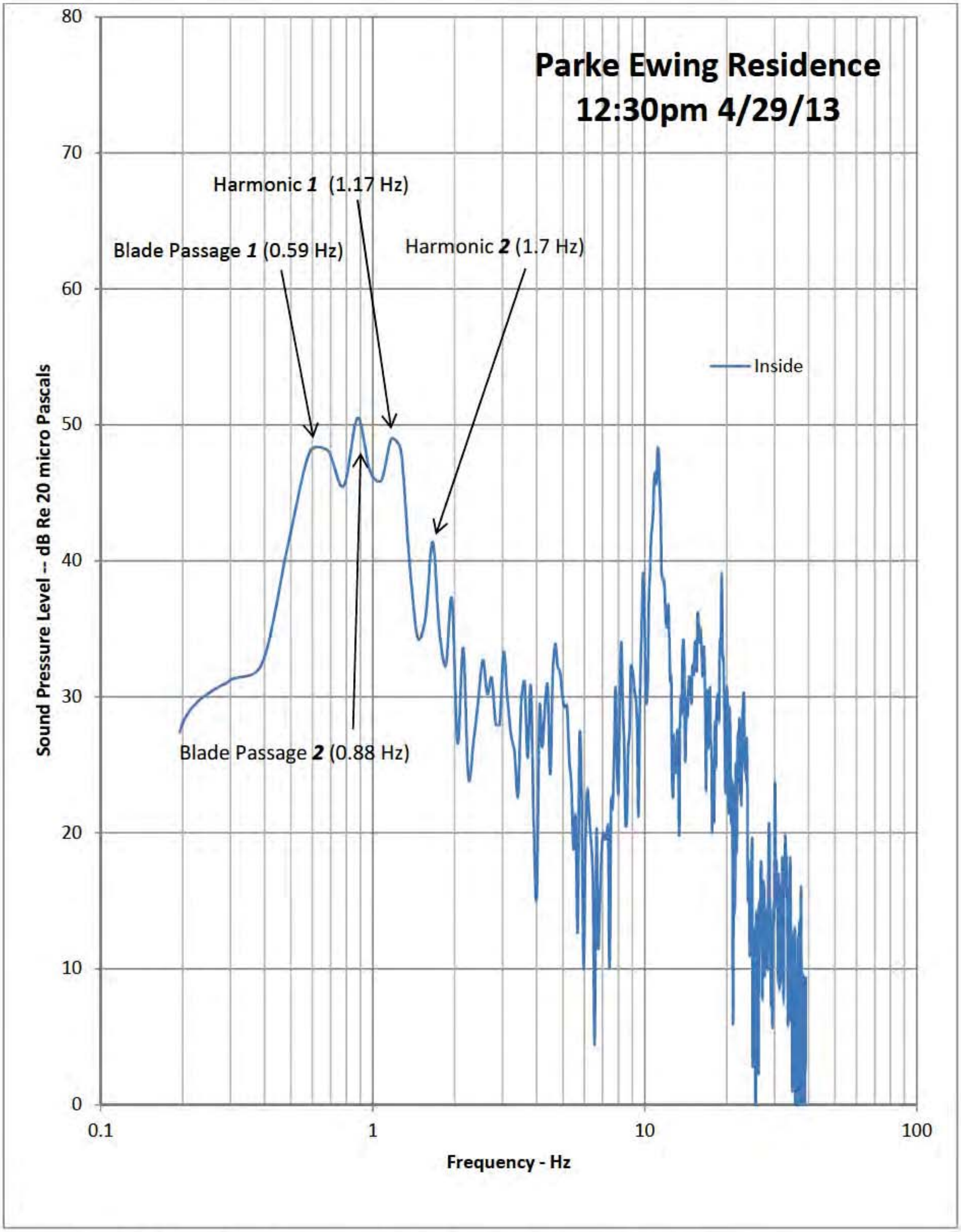

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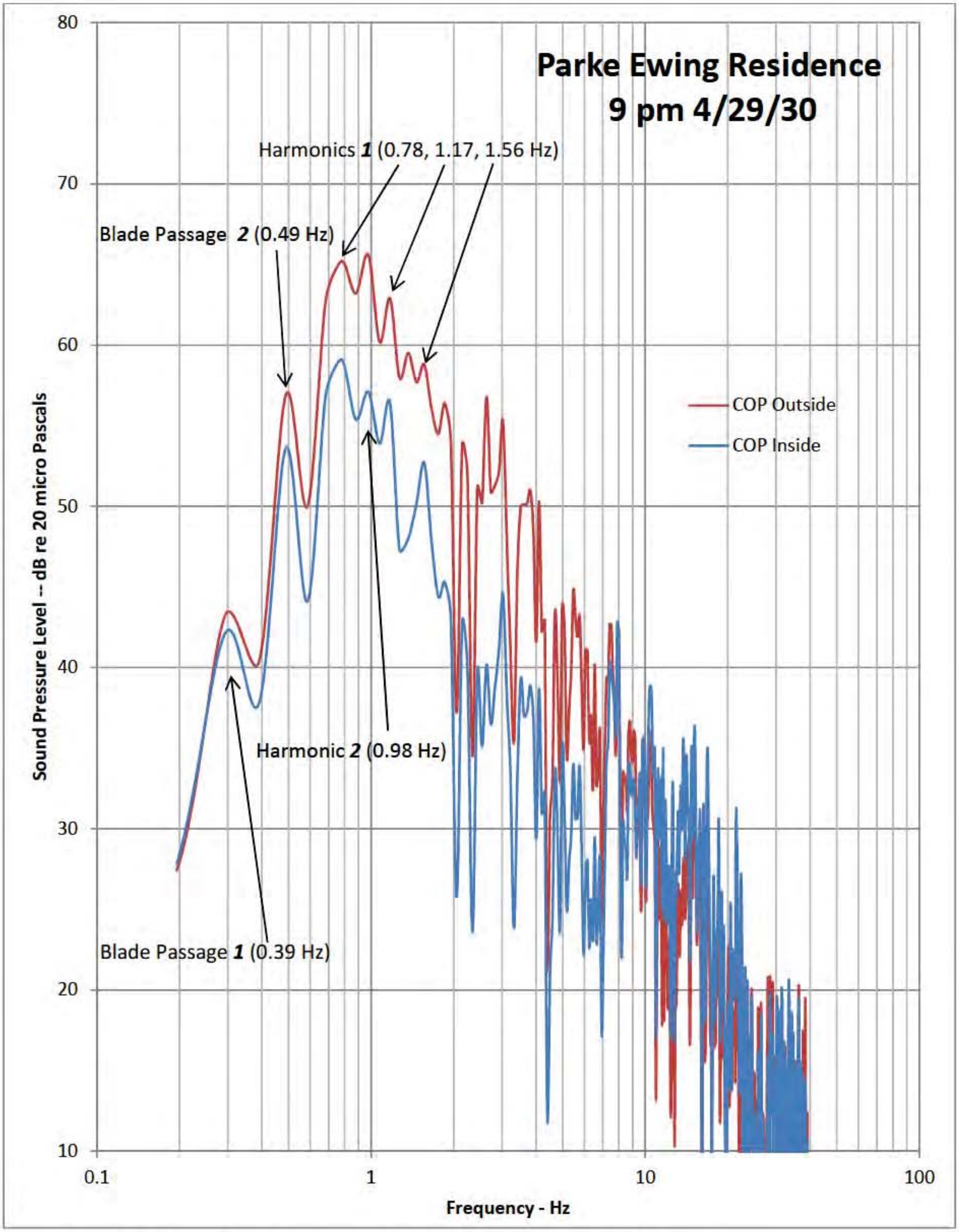

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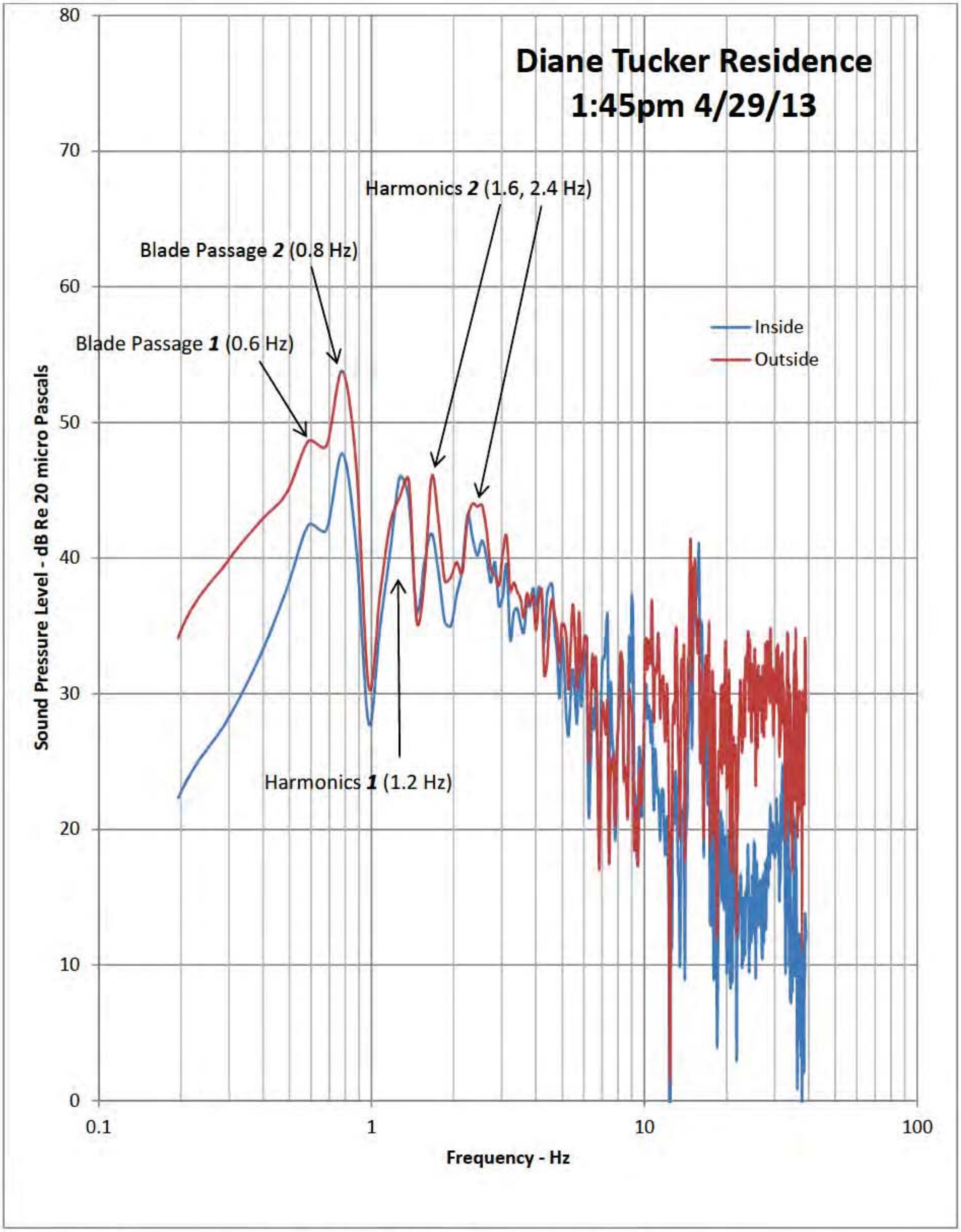

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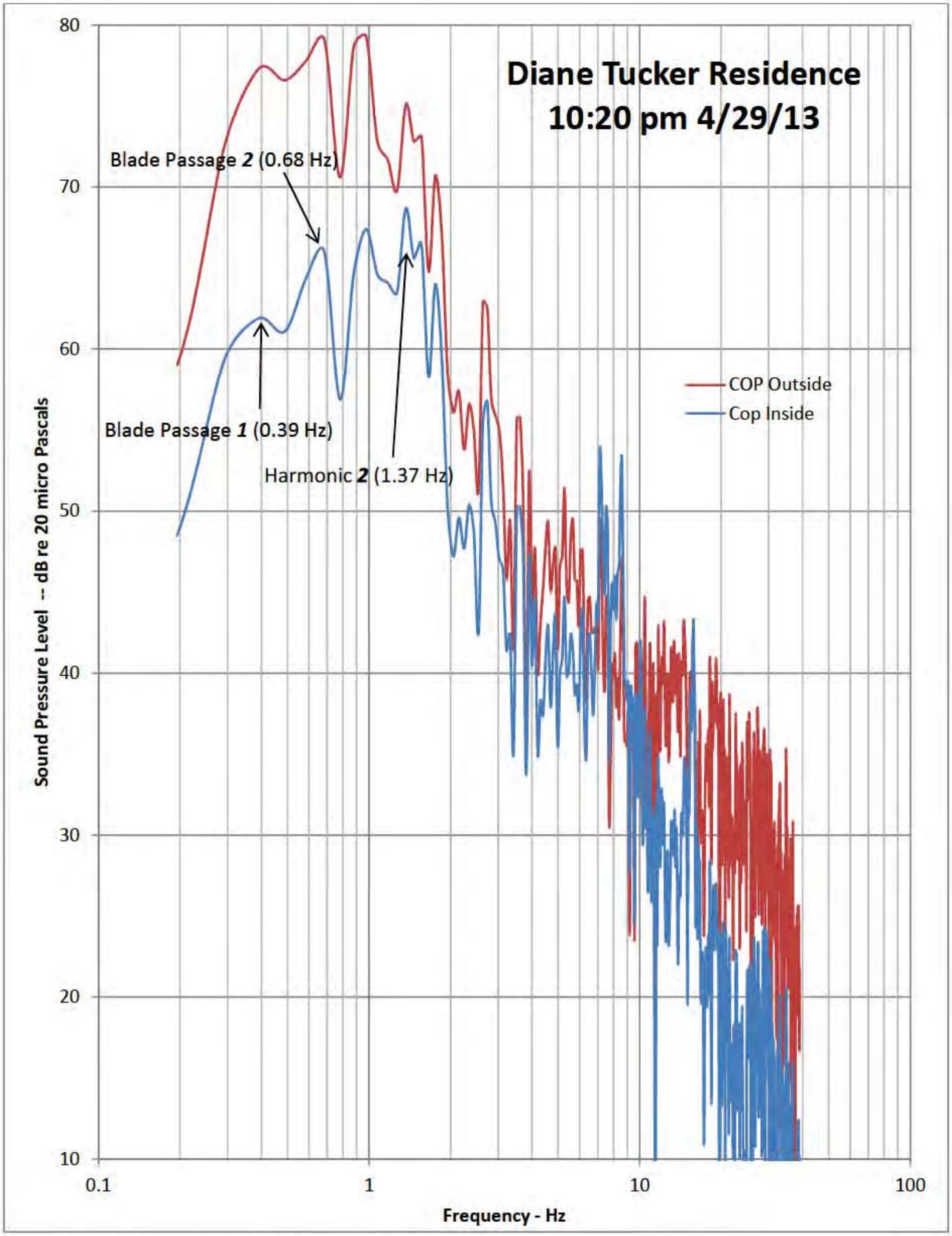

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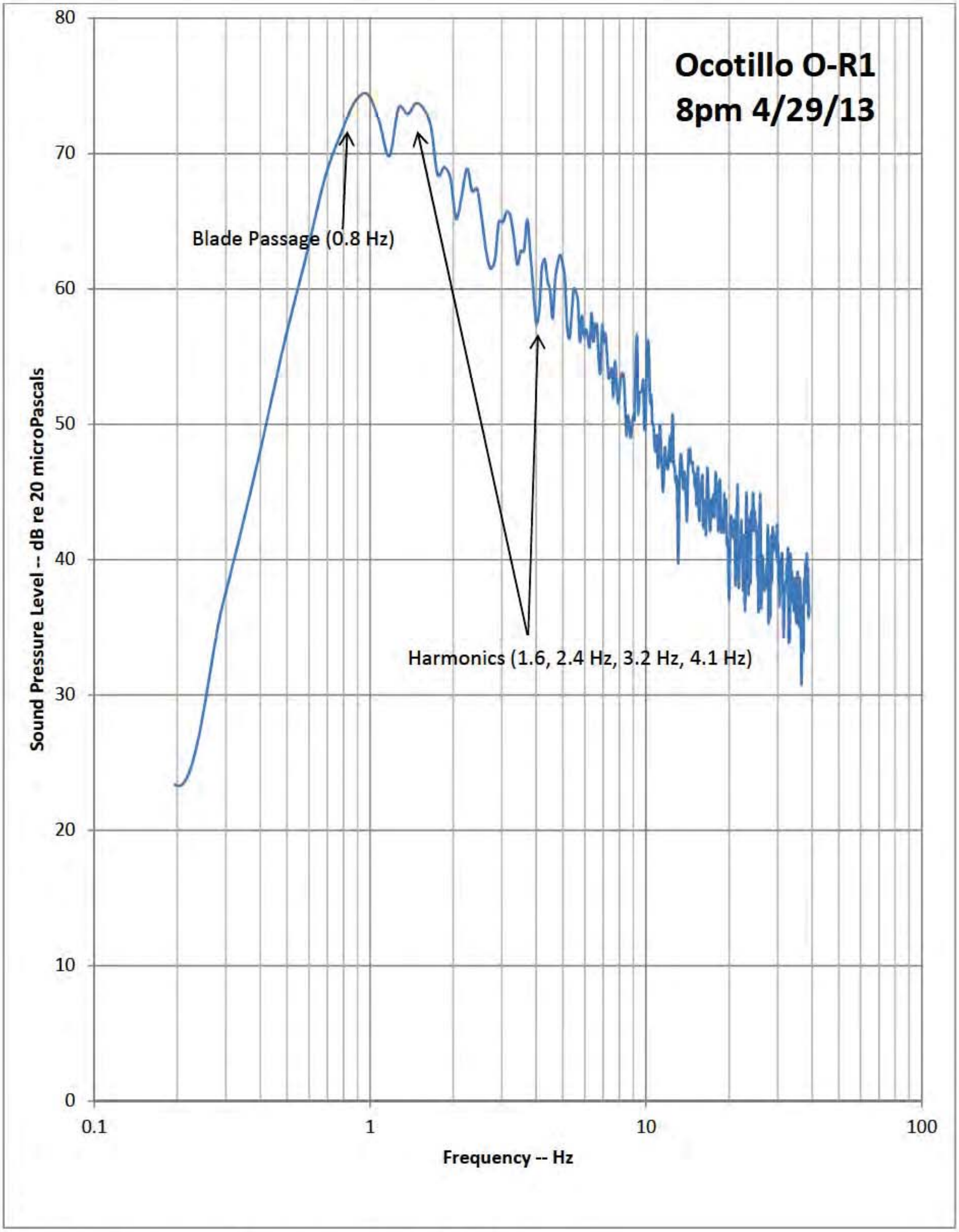

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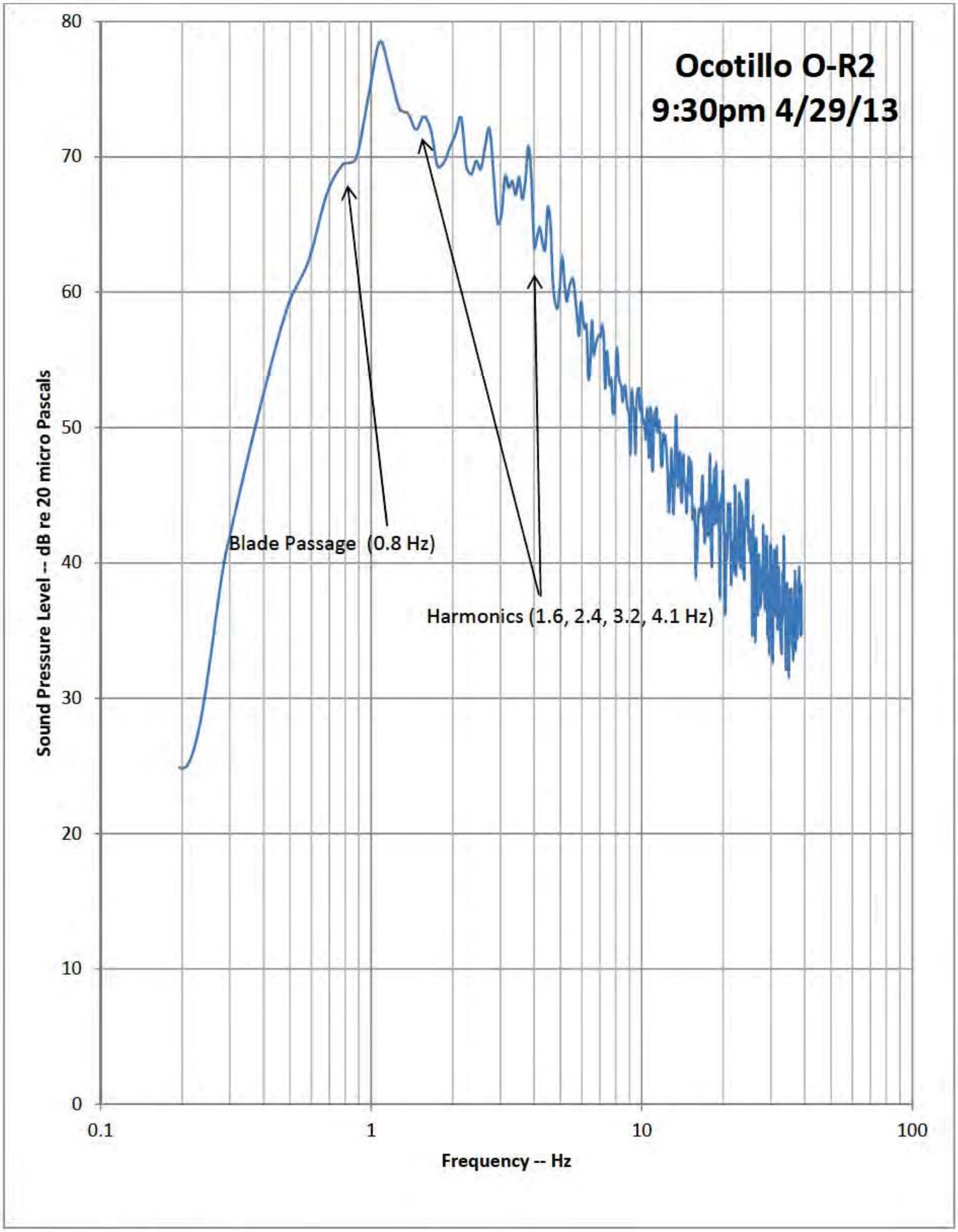

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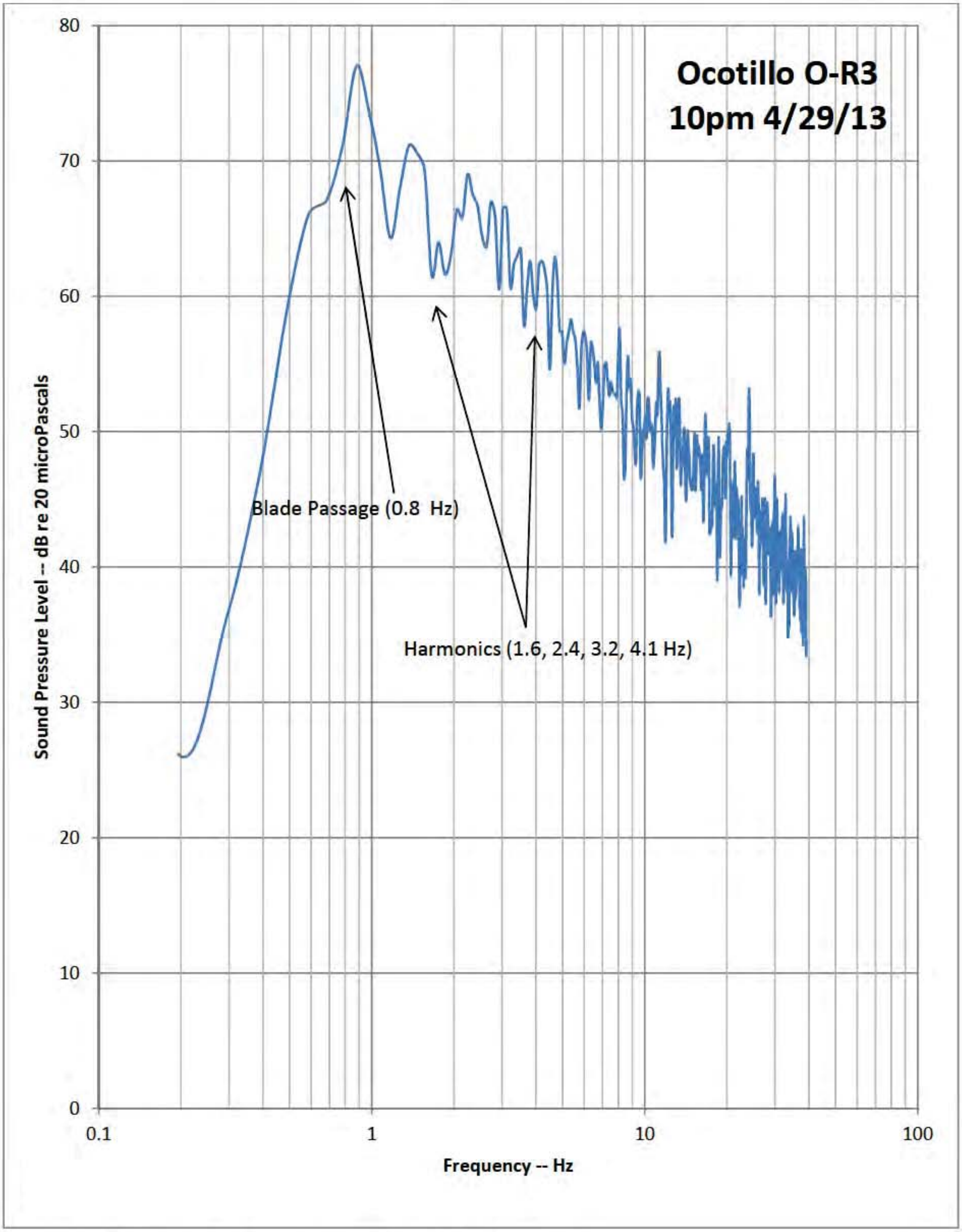

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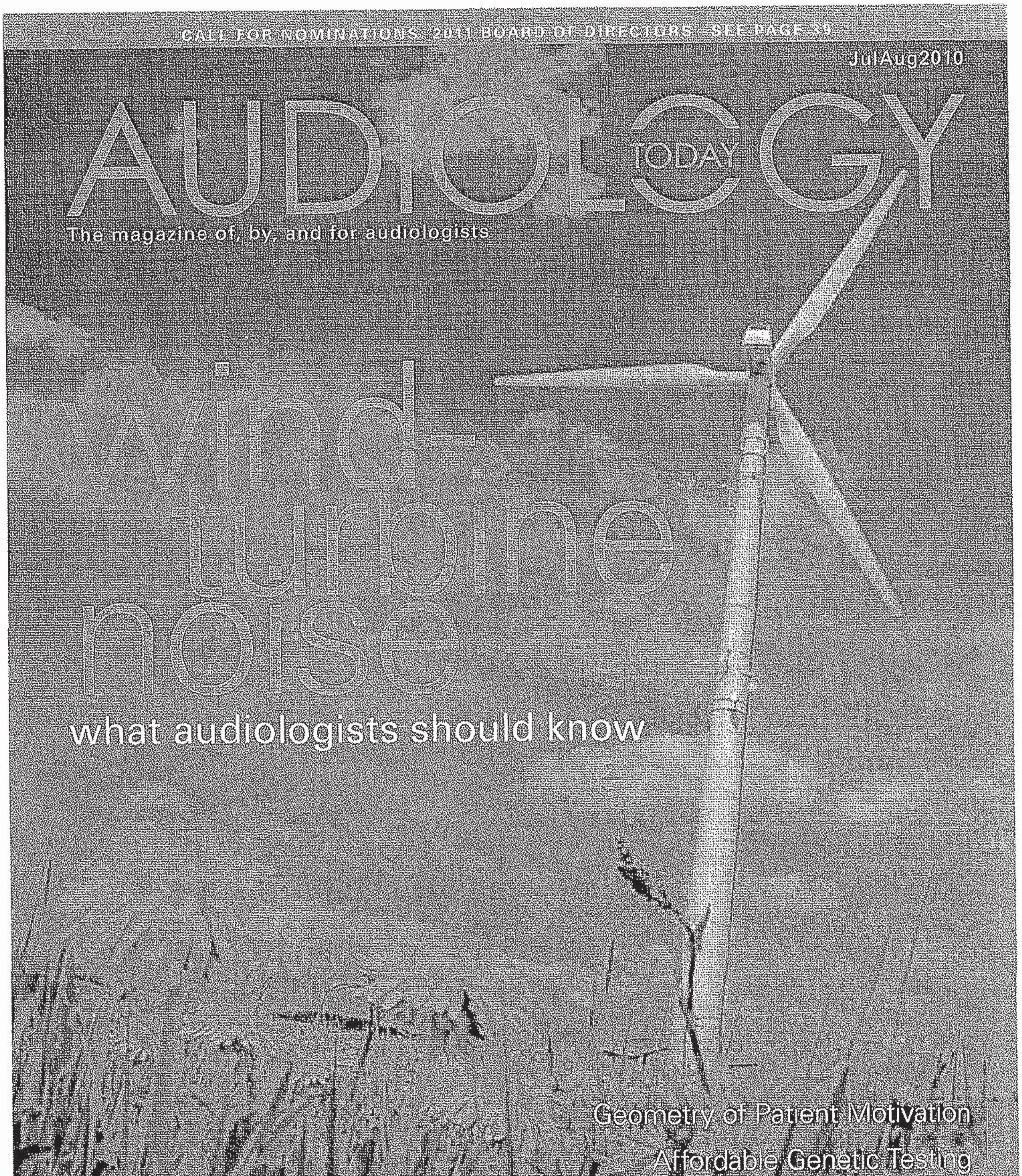

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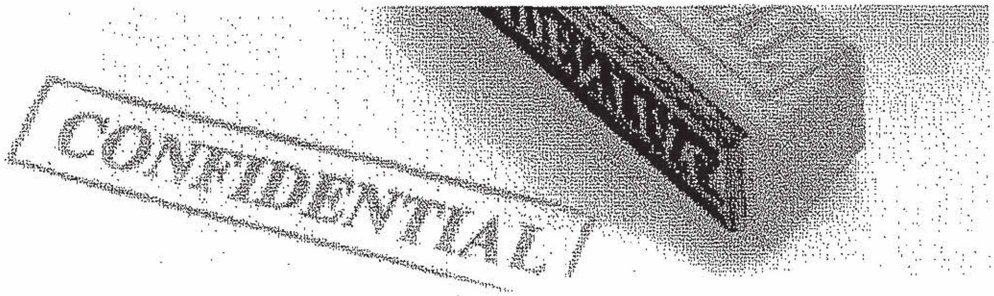

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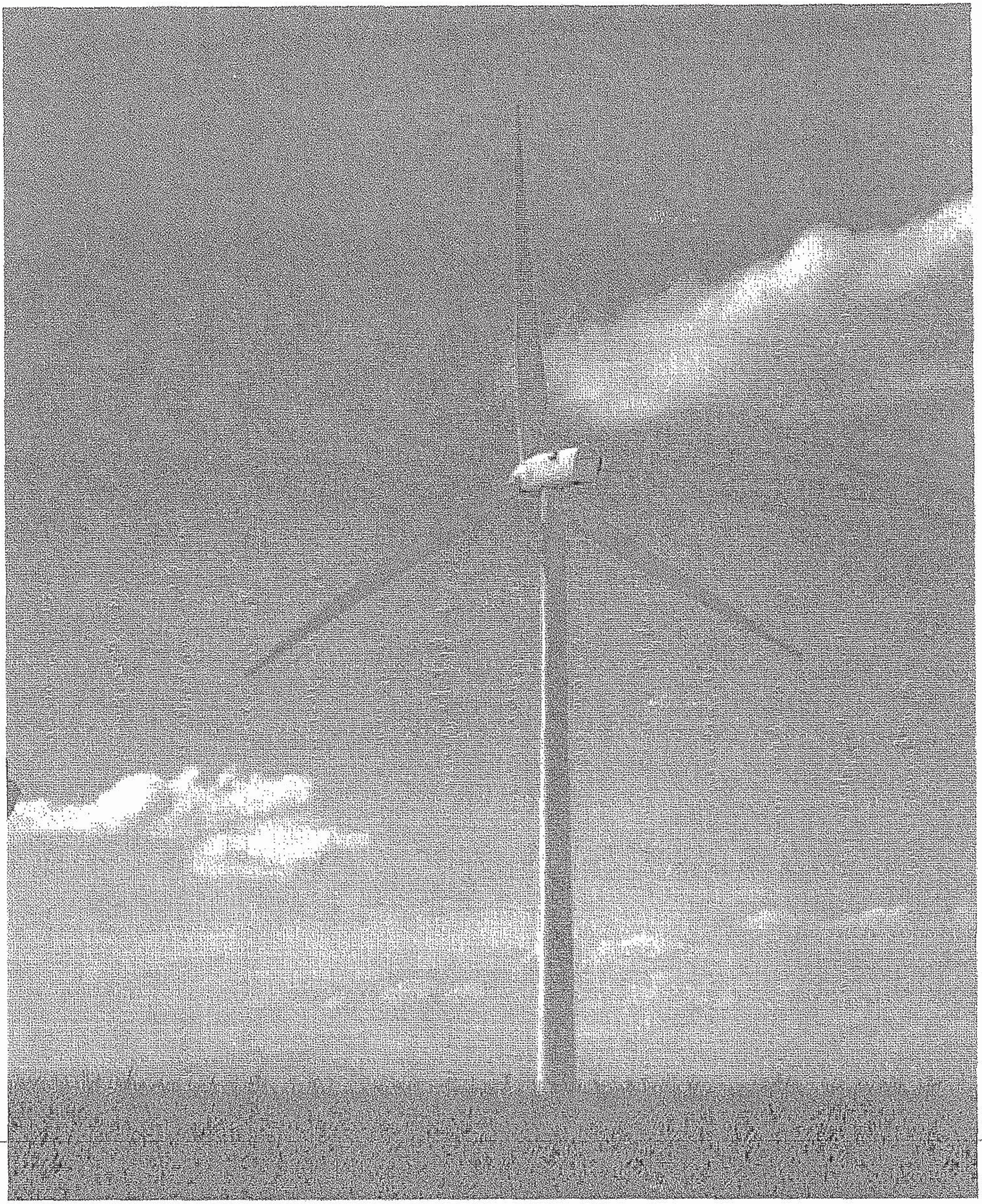
Wind-Turbine NOISE

What Audiologists Should Know

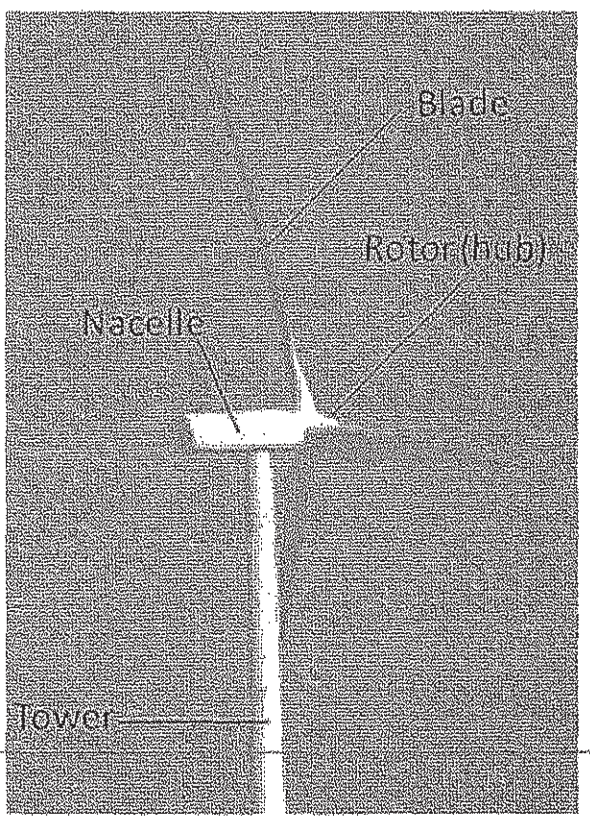
BY JERRY PUNCH, RICHARD JAMES, AND DAN PABST

Noise from modern wind turbines is not known to cause hearing loss, but the low-frequency noise and vibration emitted by wind turbines may have adverse health effects on humans and may become an important community noise concern.



Most of us would agree that the modern wind turbine is a desirable alternative for producing electrical energy. One of the most highly touted ways to meet a federal mandate that 20 percent of all energy must come from renewable sources by 2020 is to install large numbers of utility-scale wind turbines. Evidence has been mounting over the past decade, however, that these utility-scale wind turbines produce significant levels of low-frequency noise and vibration that can be highly disturbing to nearby residents.

None of these unwanted emissions, whether audible or inaudible, are believed to cause hearing loss, but they are widely known to cause sleep disturbances. Inaudible components can induce resonant vibration in solids, liquids, and gases—including the ground, houses, and other building structures, spaces within those structures, and bodily tissues and cavities—that is potentially harmful to humans. The most extreme of these low-frequency (infrasonic) emissions, at frequencies under about 16 Hz, can easily penetrate homes. Some residents perceive the energy as sound, others experience it as vibration, and others are not aware of it at all. Research is beginning to show that, in addition to sleep disturbances, these emissions may have other deleterious consequences on health. It is for these reasons that wind turbines are becoming an important community health issue, especially when hosted in quiet rural communities that have no prior experience with industrial noise or urban hum.



Major components of a modern wind turbine.

The people most susceptible to disturbances caused by wind turbines may be a small percentage of the total exposed population, but for them the introduction of wind turbines in their communities is not something to which they can easily become acclimated. Instead, they become annoyed, uncomfortable, distressed, or ill. This problem is increasing as newer utility-scale wind turbines capable of generating 1.5-5 MWatts of electricity or more replace the older turbines used over the past 30 years, which produced less than 1 MWatt of power. These large wind turbines can have hub heights that span the length of a football field and blade lengths that span half that distance. The increased size of these multi-MWatt turbines, especially the blades, has been associated with complaints of adverse health effects (AHEs) that cannot be explained by auditory responses alone.

For this article, we reviewed the English-language, peer-reviewed literature from around the world on the topic of wind-turbine noise and vibration and their effects on humans. In addition, we used popular search engines to locate relevant online trade journals, books, reference sources, government regulations, and acoustic and vibration standards. We also consulted professional engineers and psychoacousticians regarding their unpublished ideas and research.

Sources of Wind-Turbine Noise and Vibration

Physically, a modern wind turbine consists of a tower; a rotor (or hub); a set of rotating blades—usually three, located upwind to the tower; and a nacelle, which is an enclosure containing a gearbox, a generator, and computerized controls that monitor and regulate operations (FIGURE 1). Wind speed can be much greater at hub level than at ground level, so taller wind towers are used to take advantage of these higher wind speeds. Calculators are available for predicting wind speed at hub height, based on wind speeds at 10 meter weather towers, which can easily be measured directly.

Mechanical equipment inside the nacelle generates some noise, but at quieter levels than older turbines. This mechanical sound is usually considered of secondary importance in discussions of annoyance from today's turbines. The main cause of annoyance is an aerodynamic source created by interaction of the turning blades with the wind. With optimal wind conditions, this aerodynamic noise is steady and commonly described as an airplane overhead that never leaves.

When wind conditions are not optimal, such as during turbulence caused by a storm, the steady sounds are augmented by fluctuating aerodynamic sounds. Under steady wind conditions, this interaction generates a broadband whooshing sound that repeats itself about once a second and is clearly audible. Many people who live near the wind turbine find this condition to be very disturbing.

The whooshing sound comes from variations of air turbulence from hub to blade tip and the inability of the turbine to keep the blades adjusted at an optimal angle as wind direction varies. The audible portion of the whoosh is around 300 Hz, which can easily penetrate walls of homes and other buildings. In addition, the rotating blades create energy at frequencies as low as 1–2 Hz (the blade-passage frequency), with overtones of up to about 20 Hz. Although some of this low-frequency energy is audible to some people with sensitive hearing, the energy is mostly vibratory to people who react negatively to it.

Adverse Health Effects of Wind-Turbine Noise

Hubbard and Shepherd (1990), in a technical paper written for the National Aeronautics and Space Administration (NASA), were the first to report in depth on the noise and vibration from wind turbines. Most of the relevant research since that time has been conducted by European investigators, as commercial-grade (utility-scale) wind turbines have existed in Europe for many decades. Unfortunately, the research and development done by wind-turbine manufacturers is proprietary and typically has not been shared with the public, but reports of the distressing effects on people living near utility-scale wind turbines in various parts of the world are becoming more common.

Studies carried out in Denmark, The Netherlands, and Germany (Wolsink and Sprengers, 1993; Wolsink et al, 1993), a Danish study (Pedersen and Nielsen, 1994), and two Swedish studies (Pedersen and Persson Waye, 2004, 2007) collectively indicate that wind turbines differ from other sources of community noise in several respects. These investigators confirm the findings of earlier research that amplitude-modulated sound is more easily perceived and more annoying than constant-level sounds (Bradley, 1994; Bengtsson et al, 2004) and that sounds that are unpredictable and uncontrollable are more annoying than other sounds (Geen and McCown, 1984; Hatfield et al, 2002).

Annoyance from wind-turbine noise has been difficult to characterize by the use of such psychoacoustic parameters as sharpness, loudness, roughness, or modulation (Persson Waye and Öhrström, 2002). The extremely low-frequency nature of wind-turbine noise, in combination with the fluctuating blade sounds, also means that the noise is not easily masked by other environmental sounds.

Pedersen et al (2009), in a survey conducted in The Netherlands on 725 respondents, found that noise from wind turbines is more annoying than transportation or industrial noises at comparable levels, measured in dBA. They noted that annoyance from turbine sounds at 35 dBA corresponds to the annoyance reported for other common community-noise sources at 45 dBA. Higher visibility of the turbines was associated with higher levels of annoyance, and annoyance was greater when attitudes toward the visual impact of the turbines on the landscape were negative. However, the height of wind turbines means that they are also most clearly visible to the people closest to them and those who also receive the highest sound levels. Thus, proximity of the receiver to wind turbines makes it difficult to determine whether annoyance to the noise is independent of annoyance to the visual impact. Pedersen et al (2009) also found that annoyance was substantially lower in people who benefitted economically from having wind turbines located on their property.

Among audiologists and acousticians, it has been understood for many decades that sufficiently intense and prolonged exposure to environmental noise can cause hearing impairment, annoyance, or both. In essence, the view has been *what* you can hear can hurt you. In the case of wind turbines, it seems that *what* you can't hear can also hurt you. Again, there is no evidence that noise generated by wind turbines, even the largest utility-scale turbines, causes hearing loss. But there is increasingly clear evidence that audible and low-frequency acoustic energy from these turbines is sufficiently intense to cause extreme annoyance and inability to sleep, or disturbed sleep, in individuals living near them.

Table 1. Core Symptoms of Wind-Turbine Syndrome

1	Sleep disturbance
2	Headache
3	Visceral Vibratory Vestibular Disturbance (VVVD)
4	Dizziness, vertigo, unsteadiness
5	Tinnitus
6	Ear pressure or pain
7	External auditory canal sensation
8	Memory and concentration deficits
9	Irritability, anger
10	Fatigue, loss of motivation

Source: Pierpont, 2009

Jung and colleagues (2008), in a Korean study, concluded that low-frequency noise in the frequency range above 30 Hz can lead to psychological complaints and that infrasound in the frequency range of 5–8 Hz can cause complaints due to rattling doors and windows in homes.

The energy generated by large wind turbines can be especially disturbing to the vestibular systems of some people, as well as cause other troubling sensations of the head, chest, or other parts of the body. Dr. Nina Pierpont (2009), in her definitive natural experiment on the subject, refers to these effects as Wind-Turbine Syndrome (WTS). TABLE 1 lists the symptoms that, in various combinations, characterize WTS. Although hearing impairment is not one of the symptoms of WTS, audiologists whose patients report these symptoms should ask them if they live near a wind turbine.

It is well known that sleep deprivation has serious consequences, and we know that noncontinuous sounds and nighttime sounds are less tolerable than continuous and daytime sounds. Somewhat related effects, such as cardiac arrhythmias, stress, hypertension, and headaches have also been attributed to noise or vibration from wind turbines, and some researchers are referring to these effects as Vibroacoustic Disease, or VAD (Castelo Branco, 1999; Castelo Branco and Alves-Pereira, 2004). VAD is described as occurring in persons who are exposed to high-level (>90 dB SPL) infra- and low-frequency noise (ILFN), under 500 Hz, for periods of 10 years or more. It is believed to be a systemic pathology characterized by direct tissue damage to a variety of bodily organs and may involve abnormal proliferation of extracellular matrices.

Alves-Pereira and Castelo Branco (2007) reported on a family who lived near wind turbines and showed signs of VAD. The sound levels in the home were less than 60 dB SPL in each 1/3–octave band below 100 Hz. We have measured unweighted sound levels ranging from 60 to 70 dB Leq (averaged over 1 minute) in these low-frequency bands in Ontario homes of people reporting AHEs from wind turbines. A spectral analysis of sounds emitted at a Michigan site revealed that unweighted peak levels at frequencies under 5 Hz exceeded 90 dB SPL (Wade Bray, pers. comm., 2009).

Similar observations have been made in studies of people who live near busy highways and airports, which also expose people to low-frequency sounds, both outdoors and in their homes. Evidence is insufficient to substantiate that typical exposures to wind-turbine noise, even in residents who live nearby, can lead to VAD, but early indications are that there are some more-vulnerable people who may be susceptible. Because ILFN is not yet recognized as a disease agent, it is not covered by legislation, permissible exposure levels have not yet been established, and dose-response relationships are unknown (Alves-Pereira, 2007).

As distinguished from VAD, Pierpont's (2009) use of the term Wind-Turbine Syndrome appears to emphasize a constellation of symptoms due to stimulation, or overstimulation, of the vestibular organs of balance due to ILFN from wind turbines (see TABLE 1). One of the most distinctive symptoms she lists in the constellation of symptoms comprising WTS is Visceral Vibratory Vestibular Disturbance (VVVD), which she defines as "a sensation of internal quivering, vibration, or pulsation accompanied by agitation, anxiety, alarm, irritability, rapid heartbeat, nausea, and sleep disturbance" (p. 270).

Drawing on the recent work of Balaban and colleagues (i.e., Balaban and Yates, 2004), Pierpont describes the close association between the vestibular system and its neural connections to brain nuclei involved with balance processing, autonomic and somatic sensory inflow and outflow, the fear and anxiety associated with vertigo or a sudden feeling of postural instability, and aversive learning. These neurological relationships give credence to Pierpont's linkage of the symptoms of VVVD to the vestibular system.

Todd et al (2008) demonstrated that the resonant frequency of the human vestibular system is 100 Hz, concluding that the mechano-receptive hair cells of the vestibular structures of the inner ear are remarkably sensitive to low-frequency vibration and that this sensitivity to vibration exceeds that of the cochlea. Not only is 100 Hz the frequency of the peak response of the vestibular system to vibration, but it is also a frequency at which a substantial amount of acoustic energy is produced by wind turbines. Symptoms of both VAD and VVVD can presumably occur in the presence of ILFN as a result of disruptions of normal paths or structures that mediate the fine coordination between living tissue deformation and activation of signal transducers; these disruptions can lead to aberrant mechano-electrical coupling that can, in turn, lead to conditions such as heart arrhythmias (Ingber, 2008). Ultimately, further research will be needed to sort out the commonalities and differences among the symptoms variously described in the literature as VAD, VVVD, and WTS.

Dr. Geoff Leventhall, a British scientist, and his colleagues (Waye et al, 1997; Leventhall, 2003, 2004) have documented the detrimental effects of low-frequency noise exposure. They consider it to be a special environmental noise, particularly to sensitive people in their homes. Waye et al (1997) found that exposure to dynamically modulated low-frequency ventilation noise (20–200 Hz)—as opposed to midfrequency noise exposure—was more bothersome, less pleasant, impacted work performance more negatively, and led to lower social orientation.

Leventhall (2003), in reviewing the literature on the effects of exposure to low-frequency noise, found no evidence of hearing loss but substantial evidence of vibration of bodily structures (chest vibration), annoyance (especially in homes), perceptions of unpleasantness (pressure on the eardrum, unpleasant perception within the chest area, and a general feeling of vibration), sleep disturbance (reduced wakefulness), stress, reduced performance on demanding verbal tasks, and negative biological effects that included quantitative measurements of EEG activity, blood pressure, respiration, hormone production, and heart rate.

Regarding work performance, reviewed studies indicated that dynamically modulated low-frequency noise, even when inaudible to most individuals, is more difficult to ignore than mid- or high-frequency noise and that its imperviousness to habituation leads to reduced available information-processing resources. Leventhall hypothesized that low-frequency noise, therefore, may impair work performance. More recently, as a consultant on behalf of the British Wind Energy Association (BWEA), the American Wind Energy Association (AWEA), and the Canadian Wind Energy Association (CANWEA), Leventhall (2006) changed his position, stating that although wind turbines do produce significant levels of low-frequency sound, they do not pose a threat to humans—in effect reverting to the notion that *what* you can't hear can't hurt you.

According to the World Health Organization guidelines (WHO, 2007), observable effects of nighttime, outdoor wind-turbine noise do not occur at levels of 30 dBA or lower. Many rural communities have ambient, nighttime sound levels that do not exceed 25 dBA. As outdoor sound levels increase, the risk of AHEs also increases, with the most vulnerable being the first to show its effects. Vulnerable populations include elderly persons; children, especially those younger than age six; and people with pre-existing medical conditions, especially if sleep is affected. For outdoor sound levels of 40 dBA or higher, the WHO states that there is sufficient evidence to link prolonged exposure to AHEs. While the WHO identifies long-term, nighttime audible sounds over 40 dBA outside one's home as a cause of AHEs, the wind industry commonly promotes 50 dBA as a safe limit for nearby homes and properties. Recently, a limit of 45 dBA has been proposed for new wind projects in Canada (Keith et al, 2008).

Utility-scale wind turbines located in Huron County, Michigan.

Much of the answer as to why the wind industry denies that noise is a serious problem with its wind turbines is because holding the noise to 30 dBA at night has serious economic consequences. The following quotation by Upton Sinclair seems relevant here: "It is difficult to get a man to understand something when his salary depends upon his not understanding it" (Sinclair, 1935, reprinted 1994, p. 109).

In recent years, the wind industry has denied the validity of any noise complaints by people who live near its utility-scale wind turbines. Residents who are leasing their properties for the siting of turbines are generally so pleased to receive the lease payments that they seldom complain. In fact, they normally are required to sign a leasing agreement, or gag clause, stating they will not speak or write anything unfavorable about the turbines. Consequently, complaints, and sometimes lawsuits, tend to be initiated by individuals who live near property on which wind turbines are sited, and not by those who are leasing their own property. This situation pits neighbor against neighbor, which leads to antagonistic divisions within communities.

Measurement of Wind-Turbine Noise

It is important to point out that the continued use of the A-weighting scale in sound-level meters is the basis for misunderstandings that have led to acrimony between advocates and opponents of locating wind turbines in residential areas. The dBA scale grew out of the desire to incorporate a function into the measurement of sound pressure levels of environmental and industrial noise that is the inverse of the minimum audibility curve (Fletcher and Munson, 1933) at the 40-phon level. It is typically used, though, to specify the levels of noises that are more intense, where the audibility curve becomes considerably flattened, obviating the need for A-weighting. It is mandated in various national and international standards for measurements that are compared to damage-risk criteria for hearing loss and other health effects. The A-weighted scale in sound-level meters drastically reduces sound-level readings in the lower frequencies, beginning at 1000 Hz, and reduces sounds at 20 Hz by 50 dB.

For wind-turbine noise, the A-weighting scale is especially ill-suited because of its devaluation of the effects of low-frequency noise. This is why it is important to make C-weighted measurements, as well as A-weighted measurements, when considering the impact of sound from wind turbines. Theoretically, linear-scale measurements would seem superior to C-scale measurements in wind-turbine applications, but linear-scale measurements lack standardization due to failure on the part of manufacturers of sound-level meters to agree on such factors as low-frequency cutoff and response tolerance limits. The Z-scale, or zero-frequency weighting, was introduced in 2003 by the International Electro-technical Commission (IEC) in its Standard 61672 to replace the flat, or linear, weighting used by manufacturers in the past.

State of Michigan Siting Guidelines

Michigan's siting guidelines (State of Michigan, 2008) will be used as an example of guidelines that deal only in a limited way with sound. These guidelines refer to earlier, now outdated, WHO and Environmental Protection Agency (EPA) guidelines to support a noise criterion that SPLs cannot exceed 55 dBA at the adjacent property line. This level is allowed to be exceeded during severe weather or power outages, and when the ambient sound level is greater than 55 dBA, the turbine noise can exceed that higher background sound level by 5 dB. These levels are about 30 dB above the nighttime levels of most rural communities. When utility-scale turbines were installed in Huron County, Michigan, in May 2008, the WHO's 2007 guidelines that call for nighttime, outside levels not to exceed 30 dBA were already in place. Based on measurements made by the authors, these turbines produce 40–45 dBA sound levels at the perimeter of a 1,000 ft radius under typical weather conditions, and the additive effects of multiple turbines produce higher levels. Many of the turbines have been located close enough to homes to produce very noticeable noise and vibration.

Kamperman and James (2009) have offered recommendations for change in the State of Michigan guidelines (2008) for wind turbines. Some of the more pertinent details of the Michigan siting guidelines are shown in the left-hand column of TABLE 2. The state of Michigan permits sound levels that do not exceed 55 dBA or L90 + 5 dBA, whichever is greater, measured at the property line closest to the wind-energy system. These guidelines make no provisions to limit low-frequency sounds from wind-turbine operations.

In consideration of the current WHO guidelines (2007), measurements made by the authors in Huron County, Michigan, indicate that the current Michigan guidelines do not appear adequate to protect the public from the nuisances and known health risks of wind-turbine noise. In fact, these guidelines appear to be especially lenient

Table 2. Current and Proposed Wind-Turbine Siting Guidelines

Current Michigan Guidelines*	Alternative Proposed Guidelines**
Sound level cannot exceed 55 dBA or L90 + 5 dBA, whichever is greater	Operating LAeq is not to exceed the background LA90 +5 dBA, where LA90 is measured during a preconstruction noise study at the quietest time of night. Similar dBC limits should also be applied.
Limits apply to sound levels measured at homes (as stated in Huron County Ordinance)	Limits apply to sound levels measured at property lines, except that turbine sounds cannot exceed 35 dBA at any home
No provisions are made for limiting low-frequency sounds from wind-turbine operations	LCeq-LA90 cannot exceed 20 dB at receiving property, e.g., LCeq (from turbines) minus (LA90 [background] + 5) < 20 dB, and is not to exceed 55 LCeq from wind turbines (60 LCeq for properties within one mile of major heavily trafficked roads)

*Source: State of Michigan, 2008

**Source: Kamperman and James, 2009

in terms of tolerable sound levels. Sound levels that approach 20 dBA higher than natural ambient levels are considered unacceptable in most countries; Michigan permits 30 dBA increases.

In considering the health and well-being of people living near wind-turbine projects, the changes recommended by Kamperman and James (2009) would abandon the 55 dBA limit in favor of the commonly accepted criteria of L90 + 5 dBA, for both A- and C-scale readings, where L90 is the preconstruction ambient level. These recommendations also include a prohibition against any wind-turbine-related sound levels exceeding 35 dBA on receiving properties that include homes or other structures in which people sleep. Additional protections against low-frequency sound are given in the right-hand column of TABLE 2. These recommended provisions would protect residents by limiting the difference between C-weighted Leq during turbine operation and the quietest A-weighted pre-operation background sound levels, plus 5 dB, to no more than 20 dB at the property line. This level should not exceed 55 dB Leq on the C scale, or 60 dB Leq for properties within one mile of major heavily trafficked roads, which sets a higher tolerance for communities that tend to experience slightly noisier conditions.

People living near wind turbines may experience sleep disturbance.

Implementation of the recommendations of Kamperman and James would result in siting wind turbines differently than what is currently planned for future wind-turbine projects in Michigan. This change would result in sound levels at nearby properties that are much less noticeable, and much less likely to cause sleep deprivation, annoyance, and related health risks. These sound-level measurements should be made by independent acoustical engineers or knowledgeable audiologists who follow ANSI guidelines (1993, 1994) to ensure fair and accurate readings, and not by representatives of the wind industry.

People living within a mile of one or more wind turbines, and especially those living within a half mile, have frequent sleep disturbance leading to sleep deprivation, and sleep disturbances are common in people who live up to about 1.25 miles away. This is the setback distance at which a group of turbines would need to be in order not to be a nighttime noise disturbance (Kamperman and James, 2009). It is also the setback distance used in several other countries that have substantial experience with wind turbines, and is the distance at which Pierpont (2009) found very few people reporting AHEs.

A study conducted by van den Berg (2003) in The Netherlands demonstrated that daytime levels cannot be used to predict nighttime levels and that residents within 1900 mile (1.18 mile) of a wind-turbine project expressed annoyance from the noise. Pierpont (2009) recommends baseline minimum setbacks of 2 kilometers (1.24 mile) from residences and other buildings such as hospitals, schools, and nursing homes, and longer setbacks in mountainous terrain and when necessary to meet the noise criteria developed by Kamperman and James (2009).

In a panel review report, the American Wind Energy Association (AWEA) and Canadian Wind Energy Association (CANWEA) have objected to setbacks that exceed 1 mile (Colby et al, 2009). A coalition of independent medical and acoustical experts, the Society for Wind Vigilance (2010), has provided a recent rebuttal to that report. The society has described the panel review as a typical product of industry-funded white papers, being neither authoritative nor convincing. The society accepts as a medical fact that sleep disturbance, physiological stress, and psychological distress can result from exposure to wind-turbine noise.

Wind turbines have different effects on different people. Some of these effects are somewhat predictable based on financial compensation, legal restrictions on free speech included in the lease contracts with hosting landowners, and distance of the residence from wind projects, but they are sometimes totally unpredictable. Planning for wind projects needs to be directed not only toward benefitting society at large but also toward protecting the individuals living near them. We believe that the state of Michigan, and other states that have adopted similar siting guidelines for wind turbines, are not acting in the best interest of all their citizens and need to revise their siting guidelines to protect the public from possible health risks and loss of property values, as well as reduce complaints about noise annoyance.

Wind-utility developers proposing new projects to a potential host community are often asked if their projects will cause the same negative community responses that are heard from people living in the footprint of operating projects. They often respond that they will use a different type of wind turbine or that reports of complaints refer to older-style turbines that they do not use. In our opinion, these statements should usually be viewed as diversionary.

Finally, it is important to note that there is little difference in noise generated across makes and models of modern utility-scale, upwind wind turbines once their power outputs are normalized. Kamperman (pers. comm., 2009), after analyzing data from a project funded by the Danish Energy Authority (Søndergaard and Madsen, 2008), has indicated that when the A-weighted sound levels are converted to unweighted levels, the low-frequency energy from industrial wind turbines increases inversely with frequency at a rate of approximately 3 dB per octave to below 10 Hz (the lowest reported frequency). Kamperman has concluded that the amount of noise generated at low frequencies increases by 3–5 dB for every MW of electrical power generated. Because turbines are getting larger, this means that future noise problems are likely to get worse if siting guidelines are not changed.

Conclusion

Our purpose in this article has been to provide audiologists with a better understanding of the types of noise generated by wind turbines, some basic considerations underlying sound-level measurements of wind-turbine noise, and the adverse health effects on people who live near these turbines. In future years, we expect that audiologists will be called upon to make noise measurements in communities that have acquired wind turbines, or are considering them. Some of us, along with members of the medical profession, will be asked to provide legal testimony regarding our opinions on the effects of such noise on people. Many of us will likely see clinical patients who are experiencing some of the adverse health effects described in this article.

As a professional community, audiologists should become involved not only in making these measurements to corroborate the complaints of residents living near wind-turbine projects but also in developing and shaping siting guidelines that minimize the potentially adverse health effects of the noise and vibration they generate. In these ways, we can promote public health interests without opposing the use of wind turbines as a desirable and viable alternative energy source.

Jerry Punch, PhD, Richard James, BME, and Dan Pabst, BS, are with the Department of Communicative Sciences and Disorders, Michigan State University, East Lansing, MI.

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EXHIBIT 5

Wind Turbine Noise, Sleep Quality, and Symptoms of Inner Ear Problems

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Introduction

Wind turbines are a form of renewable energy, which generate electricity from wind energy, a practice dating back over 100 years. The production of electricity from the movement of wind turbine motor blades creates both mechanical and aerodynamic noise. This type of environmental noise is a growing public health concern, especially for residents living close to wind turbines. A body of evidence now exists to suggest that wind turbine noise can impair health and contribute to annoyance and sleep disturbance. However, in Ontario, little is known about how wind turbines impact people living in their vicinity. This investigation was a cross-sectional study involving eight Ontario communities that contain ten or more wind turbines. This study investigated the impact of wind turbine noise, using distance as a surrogate measure, on quality of life (both physical and mental health) and sleep disturbance in residents living close to wind turbines. Dose-response relationships were examined in an attempt to investigate acceptable exposure levels and appropriate setback distances for wind turbines.

Noise from Wind Turbines

Wind turbines produce two main types of noise:

1.Mechanical noise - mainly motor noise from within the turbine (many ways to reduce this)

2.Aerodynamic noise – mainly from the flow of air around the blades (sound pressure levels increase with tip speed and size); is the dominant source of noise from wind turbines and results in a "swishing" or "thumping" noise

Aerodynamic noise is present at all frequencies, from infrasound (frequencies below 20Hz) to low frequency (frequencies below 200 Hz) to the normal audible range. In most cases, the sound from wind turbines is described as infrasound. Although infrasound is usually inaudible, at high enough sound pressure levels, it can be audible to some people.

Studies have shown that high sound pressure levels (loudness) of audible noise and infrasound have been associated with learning, sleep and cognitive disruptions, stress, and anxiety (Leventhall et al., 2003; WHOE, 2009; Knopper & Ollson, 2011). More specifically, studies have suggested that wind turbine noise (i.e. low-frequency sound energy below 20Hz) can impact health, though this is still an area under debate (Pierpont, 2009; Salt & Hullar, 2010).

Research also suggests that some inner ear components (such as the outer hair cells) may respond to infrasound at the frequencies and sound levels generated by wind turbines. Therefore, there is a possibility that exposure to the infrasound component of wind turbine noise could influence the physiology of the ear leading to changes in the exposed individual (Salt & Hullar, 2010).

Source: http://www.psmag.com/environment/noise-complaints-draw-opposition-to-wind-farms-26673/

Acknowledgements:
This work was made possible with the support of the Ontario Research Chair for Renewable Energy Technologies and Health and the Renewable Energy Technologies and Health Research Team.

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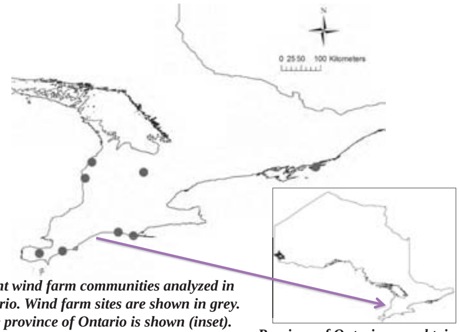


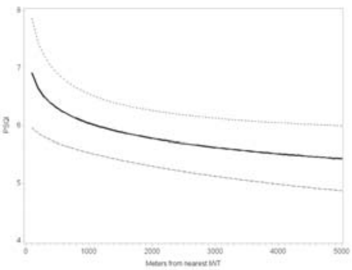
Eight wind farm communities analyzed in Ontario. Wind farm sites are shown in grey. The province of Ontario is shown (inset). (Quick et al.– submitted)

Province of Ontario map obtained from Statistics Canada.

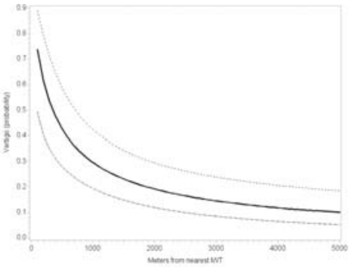
	Distance (m) from Residence to Nearest Wind Turbine (mean)			
Parameter	0-999.99 (700.62)	1000-1999.99 (1426.96)	2000-3999.99 (3044.30)	>4000 (9190.84)
Sample Size	70	80	103	143
Mean Age	52.32 (14.08)	53.95 (14.82)	55.99 (16.41)	57.09 (14.15)
Male/Female	39/30	43/37	50/52	72/68
Mean Time in Home[1]	18.38 (13.78)	20.12 (15.19)	19.76 (15.20)	18.47 (16.21)
Mean # of Wind Turbines within 2000 m	8.49 (6.47)	3.41 (2.46)	0	0

[1] Years that study participants have lived at current residence

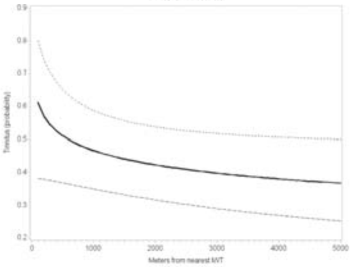
Demographic data of study participants from eight WT communities combined.



PSQI - ln(distance) relationship (P=0.0096). Graph shows modeled mean and upper and lower 95% confidence intervals.



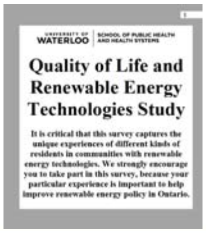
Vertigo - ln(distance) relationship (P<0.001). Graph shows modeled mean and upper and lower 95% confidence intervals.



Tinnitus - ln(distance) relationship (P=0.0755). Graph shows modeled mean and upper and lower 95% confidence intervals.

Methods

For this cross-sectional study, the "Quality of Life and Renewable Energy Technologies Study" survey was used to measure the impact of wind turbine noise on health. Using Canada Post"s Unaddressed Admail Service, surveys were sent out to 4876 residences in Ontario counties that contain 10 or more wind turbines. Completed surveys were returned to the University of Waterloo by study participants using Canada Post"s Business Reply Mail Service. Members of the Renewable Energy Technologies and Health team coded and entered the results into Microsoft Excel as surveys were received. Survey respondents"self-reported addresses (i.e. full street addresses with postal codes) were entered into Google Maps to determine the location of each residence. All analyses were performed using SAS 9.22. Descriptive and multivariate analyses were performed to investigate the effect of the main independent variable of interest (distance to nearest wind turbine) on the various outcome measures.



Results and Discussion

The data obtained for use in this study were collected between February 1st and May 31st, 2013. In total there were 412 surveys returned; 16 of these survey respondents did not provide their home address. Therefore, 396 surveys were included in the analysis.

The relationship between ln(distance) (as a continuous variable) and mean Pittsburgh Sleep Quality Index (PSQI) was found to be statistically significant (P=0.0096) when controlling for age, gender and county. This relationship shows that as the distance increases (move further away from a wind turbine), PSQI decreases (i.e. sleep improves) in a logarithmic relationship. Multivariate analysis involved assessing distance to the nearest wind turbine as both distance and ln(distance). In all cases, ln(distance) resulted in improved model fit.

The relationship between vertigo and ln(distance) was statistically significant (P<0.001) when controlling for age, gender, and county. The relationship between tinnitus and ln(distance) approached statistical significance (P=0.0755). Both vertigo and tinnitus were worse among participants living closer to wind turbines.

Spearman"s rank correlation coefficients (r_s) between PSQI, vertigo and tinnitus are shown below. All relationships were found to be positive and statistically significant. The strongest correlation was seen between the variables „tinnitus" and „vertigo"(r_s=0.2).

	Vertigo	Tinnitus	PSQI
Vertigo	1	0.25 (p<0.0001)	0.22 (p<0.0001)
Tinnitus	0.25 (p<0.0001)	1	0.11 (p=0.0392)
PSQI	0.22 (p<0.0001)	0.11 (p=0.0382)	1

In conclusion, relationships were found between ln(distance) and PSQI, ln(distance) and self-reported vertigo and ln(distance) and self-reported tinnitus. Study findings suggest that future research should focus on the effects of wind turbine noise on sleep disturbance and symptoms of inner ear problems.

County	Wind Farm	Total Surveys Sent
Bruce	Enbridge	828
Chatham-Kent	Raleigh	415
Dufferin	Melancthon	944
Elgin	Erie Shores	726
Essex	Comber	1222
Frontenac	Wolfe Island	155
Huron	Kingsbridge	473
Norfolk	Frogmore/Cultus /Clear Creek	113
TOTAL		**4876**

EXHIBIT 6

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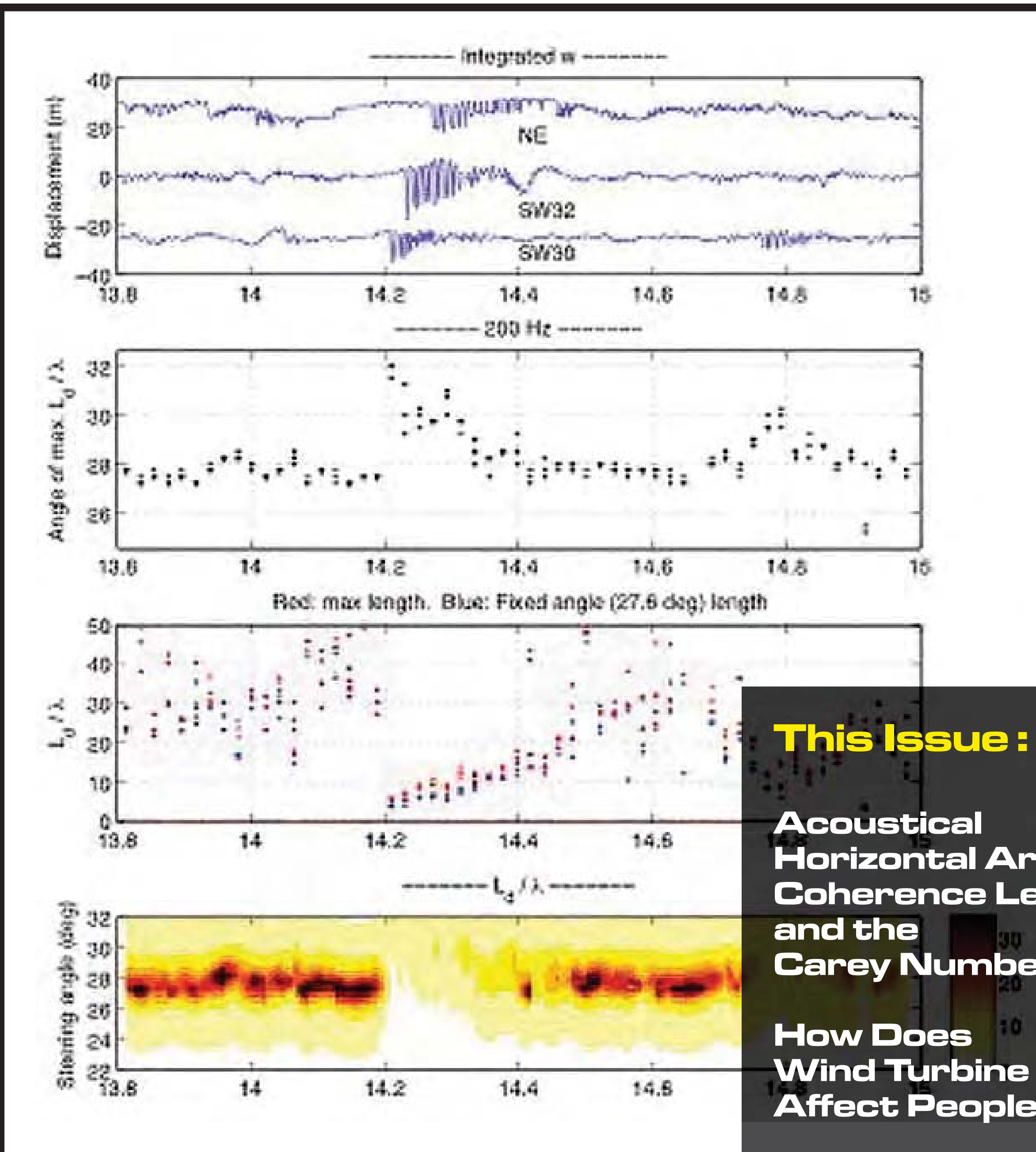

This Issue:

Acoustical Horizontal Array Coherence Lengths and the Carey Number

How Does Wind Turbine Noise Affect People?

Exploring Our Sonic Environment Through Soundscape Research & Theory

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How Does Wind Turbine Noise Affect People?

The many ways by which unheard infrasound and low-frequency sound from wind turbines could distress people living nearby are described.

Introduction

Recent articles in *Acoustics Today* have reviewed a number of difficult issues concerning wind turbine noise and how it can affect people living nearby (Leventhall 2013, Schomer 2013; Timmerman 2013). Here we present potential mechanisms by which effects could occur.

The essence of the current debate is that on one hand you have the well-funded wind industry **1.** advocating that infrasound be ignored because the measured levels are below the threshold of human hearing, allowing noise levels to be adequately documented through A-weighted sound measurements, **2.** dismissing the possibility that any variants of wind turbine syndrome exist (Pierpont 2009) even when physicians (e.g., Steven D. Rauch, M.D. at Harvard Medical School) cannot otherwise explain some patients' symptoms, and, **3.** arguing that it is unnecessary to separate wind turbines and homes based on prevailing sound levels.

On the other hand you have many people who claim to be so distressed by the effects of wind-turbine noise that they cannot tolerate living in their homes. Some move away, either at financial loss or bought-out by the turbine operators. Others live with the discomfort, often requiring medical therapies to deal with their symptoms. Some, even members of the same family, may be unaffected. Below is a description of the disturbance experienced by a woman in Europe we received a few weeks ago as part of an unsolicited e-mail.

"From the moment that the turbines began working I experienced vertigo-like symptoms on an ongoing basis. In many respects, what I am experiencing now is actually worse than the 'dizziness' I have previously experienced, as the associated nausea is much more intense. For me the pulsating, humming, noise that the turbines emit is the predominant sound that I hear and that really seems to affect me.

While the Chief Scientist [the person who came to take sound measurements in her house] undertaking the measurement informed me that he was aware of the low frequency hum the turbines produced (he lives close to a wind farm himself and had recorded the humming noise levels indoors in his own home) he advised that I could tune this noise out and that any adverse symptoms I was experiencing were simply psychosomatic."

"Almost all measurements of wind turbine noise are A-weighted, making the unjusti ed assumption that hearing is the only way by which infrasound generates physiologic effects."

We asked how she felt when she was away from the wind turbines, to which she replied:

"I did manage to take a vacation towards the end of August and for the two weeks we were away I was perfectly fine."

The goal of our work in this field is to understand whether the physiology of the ear can, or cannot, explain the symptoms people attribute to wind turbine noise. As it is generally the case when debate influences a specific industry's financial interests and legal well-being, the scientific objectivity of those associated with the industry can be questioned. Liability, damage claims, and large amounts of money can hang in the balance of results from empirical studies. Whether it is a chemical industry blamed for contaminating groundwater with cancer-causing dioxin, the tobacco industry accused of contributing to lung cancer, or athletes of the National Football League (NFL) putatively being susceptible to brain damage, it can be extremely difficult to establish the truth when some have an agenda to protect the status quo. It is only when sufficient scientific evidence is compiled by those not working for the industry that the issue is considered seriously.

Origins of Our Involvement in Infrasound from Wind Turbines

What is the evidence leading us to conclude that unheard infrasounds are part of the wind turbine problem, and how did we become involved in this debate? We are small group of basic and applied scientists, which means that our work addresses fundamental questions on how the ear works in normal and diseased states. While developing paradigms for our studies, we had been using a classic technique called "low-frequency biasing" – measurement of auditory responses to a test sound within the range of audibility, while simultaneously presenting a low-frequency tone (e.g., 4.8 to 50 Hz) to displace the sensory organ of the inner ear. Some auditory responses saturate when displaced by the bias tone, which can be used to establish whether the sensory organ is vibrating symmetrically or whether a fluid disturbance has displaced it to one side. A condition called "endolymphatic hydrops," which is found in humans with Ménière's disease, can displace the sensory organ as the space containing the fluid called endolymph swells. In our animal experiments we initially used 20 to 50 Hz bias tones, but for many reasons, and in large part based on a study in which we found that the ear responded down to 1 Hz (Salt and DeMott, 1999), we started using the lowest frequency our hardware could generate, 4.8 Hz, a frequency considered to be infrasound. Over the course of hundreds of experiments, we have found numerous biasing effects with 4.8 Hz tones at levels of 80 to 90 dB SPL (i.e., -13 to -3 dBA). We also found that the ear became about 20 dB more sensitive to infrasonic bias tones when the fluid spaces in the cochlear apex were partially occluded, as occurs with endolymphatic hydrops.

In late 2009, the first author received a report of a woman with Ménière's disease whose symptoms – primarily dizziness and nausea – were severely exacerbated when she was in the vicinity of wind turbines. From our animal data, we knew this woman was likely hypersensitive to very low-frequency sounds. Our subsequent review of the literature on wind-turbine noise revealed two aspects that were absolutely astounding:

1. Almost all measurements of wind turbine noise are A-weighted, making the unjustified assumption that hearing is the only way by which infrasound generates physiologic effects. The few studies that reported un-weighted measurements of wind-turbine noise, or recalculated spectra by removing the A-weighting from published A-weighted spectra, clearly demonstrated increasing energy towards low frequencies with highest energy levels in the infrasound region. We were surprised that objective full-frequency measurements showed that wind turbines generate infrasound at levels capable of stimulating the ear in various ways. Under such circumstances, A-weighting measurements of turbine noise would be highly misleading.

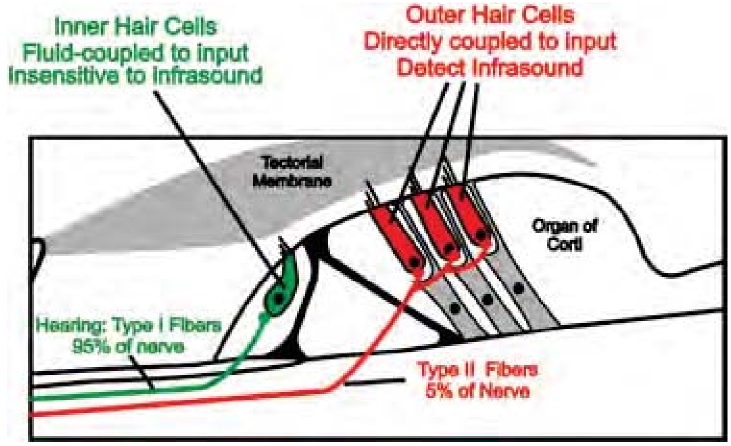


Figure 1 : The sensory organ of the cochlea, showing inner and outer hair cell and neural anatomy.

2. Literature and websites from the wind industry often contained strong statements that wind turbine infrasound was of no significance. This view was largely based on publications by Leventhall (2006; 2007). Wind turbine noise was described as comparable to rustling leaves, flowing streams, air-conditioned offices or refrigerators heard from the next room. If wind turbine noise really was comparable to such sources then complaints would not be expected. But the turbines sounds are only comparable to these sources if the ultra-low frequencies emitted by the turbines are ignored through A-weighting. Stations that monitor infrasound or low frequency seismic (vibrational) noise for other purposes (for the detection of explosions, meteors, volcanic activity, atmospheric activity, etc.) are well-aware that low frequency sounds emanating from distant wind farms, or coupling to the ground as vibrations, can influence their measurements. The UK, Ministry of Defense has opposed wind turbines cited within 50 km of the Eskdalemuir Seismic Array. We have seen no reports of the Ministry opposing the presence of refrigerators in the region, suggesting they appreciate that sounds emitted from wind turbines and refrigerators are quite different. It was thus quite astounding to see the vast majority of wind turbine noise measurements excluding the low frequency noise content. Given the knowledge that the ear responds to low frequency sounds and infrasound, we knew that comparisons with benign sources were invalid and the logic to A-weight sound measurements was deeply flawed scientifically.

The Ear's Response to Infrasound

Experimental measurements show robust electrical responses from the cochlea in response to infrasound (Salt and DeMott, 1999; Salt and Lichtenhan 2013). This finding was initially difficult to reconcile with measures showing that hearing was notably insensitive to such sounds but the explanation became clear from now-classic physiological studies of the ear showing that the two types of sensory cell in the cochlea had very different mechanical properties (Cheatham and Dallos 2001).

The auditory portion of the inner ear, the cochlea, has two types of sensory cell. The inner hair cells (IHC; shown green in *Figure 1*) are innervated by type I afferent nerve fibers that mediate hearing. The stereocilia (sensory hairs) of the IHCs are free-floating and do not contact the overlying gelatinous tectorial membrane (shown gray). They are mechanically displaced by fluid movements in the space below the membrane. As their input is fluid-coupled to the vibrations of the sensory organ they exhibit "velocity sensitive" responses. As the velocity of motions decreases for lower-frequency sounds, their fluid-coupled input renders the IHC insensitive to very low-frequency sounds. The other type of sensory cell, the outer hair cells (OHC; shown red in *Figure 1*) are innervated by type II afferent nerve fibers that are not as well understood as type I fibers and probably do not mediate conscious hearing per se. In contrast to the IHC, the stereocilia of the OHCs are inserted into the tectorial membrane. This direct mechanical coupling gives them "displacement sensitive" properties, meaning they respond well to low–frequency sounds and infrasound. The electrical responses of the ear we had been recording and studying originate from the sensitive OHCs. From this understanding we conclude that very low frequency sounds and infrasound, at levels well below those that are heard, readily stimulate the cochlea. Low frequency sounds and infrasound from wind turbines can therefore stimulate the ear at levels well below those that are heard.

The million-dollar question is whether the effects of wind turbine infrasound stimulation stay confined to the ear and have no other influence on the person or animal. At present, the stance of wind industry and its acoustician advisors is that there are no consequences to long-term low-frequency and infrasonic stimulation. This is not based on studies showing that long-term stimulation to low-level infrasound has no influence on humans or animals. No such studies have ever been performed. Their narrow perspective shows a remarkable lack of understanding of the sophistication of biological systems and is almost certainly incorrect. As we consider below, there are many physiologic mechanisms by which long-term infrasound stimulation of the cochlea could have effects.

One important aspect of wind turbine noise that is relevant to its physiological consequences is that the duration of exposure can be extremely long, 24 hours a day and lasting for days or longer, depending on prevailing wind conditions. This is considerably different from most industrial noise where 8 hour exposures are typically considered, interspersed by prolonged periods of quiet (i.e., quiet for 16 hours per day plus all weekends). There are numerous studies of exposures to higher level infrasound for periods of a few hours, but to date there have been no systematic studies of exposure to infrasound for a prolonged period. The degree of low-frequency cochlear stimulation generated by wind turbine noise is remarkably difficult to assess, due to the almost exclusive reporting of A-weighted sound level measurements. It certainly cannot be assumed that cochlear stimulation is negligible because A-weighted level measurements are low. For example, with 5 Hz stimulation cochlear responses are generated at -30 dBA and stimulation is sufficient to cause responses to saturate (indicating the transducer is being driven to its limit) at approximately 20 dBA (Salt and Lichtenhan, 2012; Salt et al., 2013). We have also shown that 125 Hz low-pass filtered noise at just 45 dBA produces larger responses than wide band noise with the same low-frequency content presented at 90 dBA (Salt and Lichtenhan 2012). We conclude that low frequency regions of the ear will be moderately to strongly stimulated for prolonged periods by wind turbine noise. There are a number of plausible mechanisms by which the stimulation could have effects:

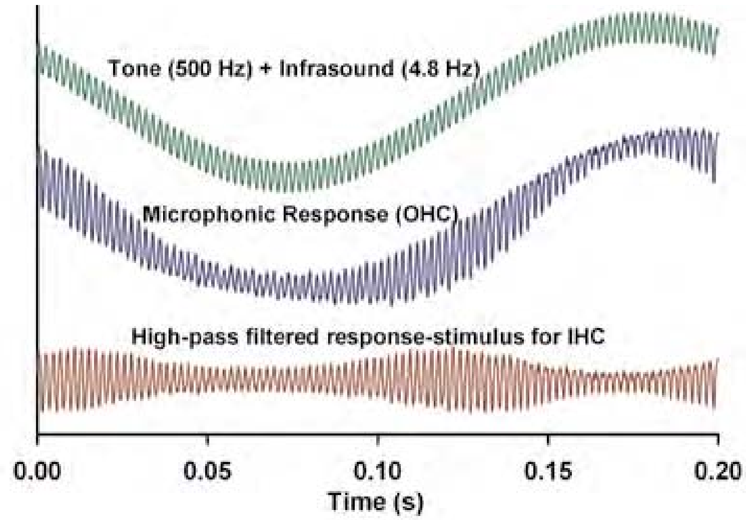


Figure 2 : *Demonstration of biologically-generated amplitude modulation to a non-modulated stimulus consisting of an audible tone at 500 Hz tone summed with an infrasonic tone at 4.8 Hz. The cochlear microphonic response, which is generated by the OHC, includes low and high frequency components. The IHC detect only the high frequency component, which is amplitude modulated at twice the infrasound frequency for the stimuli in this example.*

1. Amplitude Modulation: Low-Frequency Biasing of Audible Sounds

Modulation of the biological mechano-electric transducer of the inner ear by infrasound is completely different from the amplitude modulation of audible sounds that can be measured with a sound level meter near wind turbines under some conditions. This can be demonstrated in low-frequency biasing paradigms in which a low-frequency tone and higher-frequency audible tone are presented simultaneously to a subject.

OHCs respond to both low- and high-frequency components and modulate the high-frequency components by either saturation of the mechano-electric transducer or by cyclically changing the mechanical amplification of high frequencies. IHCs, being insensitive to the low-frequency tone, see a high pass-filtered representation of the OHC response – an amplitude modulated version of the audible probe tone, as shown in *Figure 2*. As hearing is mediated through the IHCs that receive approximately 90-95% of afferent innervation of the auditory nerve, the subject hears the higher-frequency probe tone varying in amplitude, or loudness. A similar biasing influence on cochlear responses evoked by low-level tone pips was explained by the low-frequency bias tone changing OHC-based cochlear amplifier gain (Lichtenhan 2012). This same study also showed that the low frequency, apical regions of the ear were most sensitive to low-frequency biasing. Studies like this raise the possibility that the amplitude modulation of sounds, which people living near wind turbines report

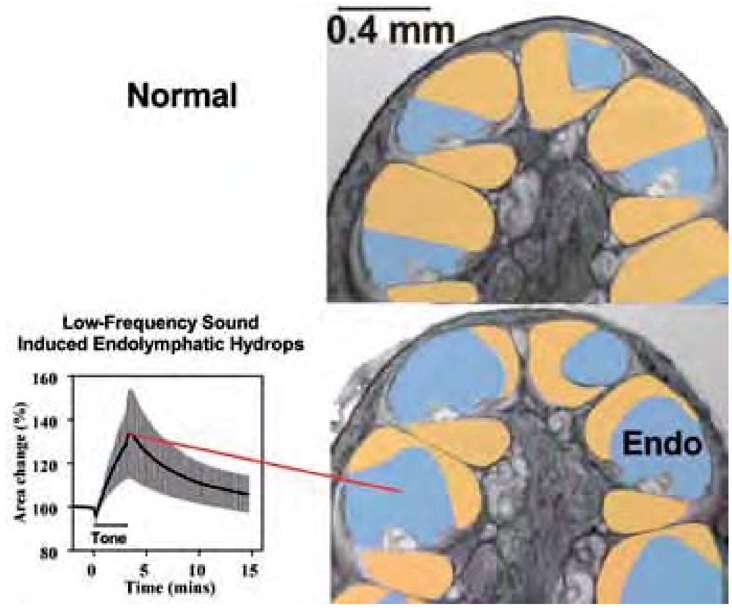


Figure 3 : *Brief exposures to low-frequency tones cause endolymphatic hydrops in animals (Salt, 2004) and tinnitus and acoustic emission changes consistent with endolymphatic hydrops in humans (Drexel et al, 2013). The anatomic pictures at the right show the difference between the normal (upper) and hydropic (lower) cochleae The endolymphatic space (shown blue) is enlarged in the hydropic cochlea, generated surgically in this case.*

as being so highly annoying, may not be easily explained by measurements with an A-weighted sound level meter. Rather, the low-frequency and infrasound levels need to be considered as contributing to the perceived phenomenon. Subjectively, the perceived fluctuation from an amplitude modulated sound and from a low-frequency biased sound are identical even though their mechanisms of generation are completely different. For the subject, the summed effects of both types of amplitude modulation will contribute to their perception of modulation. Acousticians therefore need to be aware that the degree of modulation perceived by humans and animals living near wind turbines may exceed that detected by a sound level meter.

2. Endolymphatic Hydrops Induced by Low Frequency Tones

As mentioned above, endolymphatic hydrops is a swelling of the innermost, membrane bound fluid compartment of the inner ear. Low-frequency tones presented at moderate to moderately-intense levels for just 1.5 to 3 minutes can induce hydrops *(Figure 3)*, tinnitus (ringing in the ears) and changes in auditory potentials and acoustic emissions that are physiological hallmarks of endolymphatic hydrops (Salt, 2004, Drexl et al. 2013).

Unlike the hearing loss caused by loud sounds, the symptoms resulting from endolymphatic hydrops are not permanent and can disappear, or at least fluctuate, as the degree of hydrops changes. Return to quiet *(as in Figure 3)* or relocation away from the low-frequency noise environment allow the hydrops, and the symptoms of hydrops, to resolve. This which would be consistent with the woman's description of her symptoms given earlier. As hydrops is a mechanical swelling of the membrane-bound endolymphatic space, it affects the most distensible regions first – known to be the cochlear apex and vestibular sacculus. Patients with saccular disturbances typically experience a sensation of subjective vertigo, which would be accompanied by unsteadiness and nausea. As we mentioned above, an ear that has developed endolymphatic low frequencies – has to be considered. To date, all studies of low-frequency tone-induced hydrops have used very short duration (1-2 min) exposures. In humans, this is partly due to ethical concerns about the potential long-term consequences of more prolonged exposures (Drexel et al., 2013). Endolymphatic hydrops induced by prolonged exposures to moderate levels of low-frequency sound therefore remains a real possibility.

3. Excitation of Outer Hair Cell Afferent Nerve Pathways

Approximately 5-10% of the afferent nerve fibers (which send signals from the cochlea to the brain - the type II fibers mentioned above) synapse on OHCs. These fibers do not respond well to sounds in the normal acoustic range and they are not considered to be associated with conscious hearing. Excitation of the fibers may generate other percepts, such as feelings of aural fullness or tinnitus. Moreover, it appears that infrasound is the ideal stimulus to excite OHC afferent fibers given what has been learned about these neurons from *in vitro* recordings (Weisz et al, 2012; Lichtenhan and Salt, 2013). *In vivo* excitation of OHC afferents has yet to be attempted with infrasound, but comparable fibers in birds have been shown to be highly sensitive to infrasound (Schermuly and Klinke, 1990). OHC afferents innervate cells of the cochlear nucleus that have a role in selective attention and alerting, which may explain the sleep disturbances that some people living

"The million-dollar question is whether the effects of wind turbine infrasound stimulation stay confined to the ear and have no other influence on the person or animal."

near wind turbines report (Nissenbaum et al. 2012). The likelihood that OHC afferents are involved in the effects of low-frequency noise is further supported by observations that type II innervation is greatest in the low-frequency cochlear regions that are excited most by infrasound (Liberman et al. 1990, Salt et al. 2009).

4. Exacerbation of Noise Induced Hearing Loss

Some years ago we performed experiments to test a hypothesis that infrasound was protective against noise damage (Harding et al. 2007). We reasoned that low-frequency biasing would periodically close the mechano-electric transducer channels of the sensory organ (reducing electrical responses as shown in the biasing studies above), and consequently reduce the amount of time that hair cells were exposed to the damaging overstimulation associated with noise exposure. The experimental study found that just the opposite was true. We found that simultaneous presentation of infrasound and loud noise actually exacerbated noise-induced lesions, as compared to when loud noise was presented without infrasound. Our interpretation was that low-frequency sound produced an intermixing of fluids (endolymph and perilymph) at the sites of hair cell loss resulting in lesions that were larger. A possibility to be considered is therefore that long-term exposure to infrasound from wind turbines could exacerbate presbycusis and noise-induced hearing loss. Because these forms of hearing loss develop and progress slowly over decades, this could be a lurking consequence to human exposures to infrasound that will take years to become apparent.

5. Infrasound Stimulation of the Vestibular Sense Organs

Recent exchanges in this journal between Drs. Leventhall and Schomer concerning the direct stimulation of vestibular receptors by sound at low and infrasonic frequencies deserve comment. Dr. Leventhall asserts that both Drs. Schomer and Pierpont are incorrect in suggesting that wind turbine infrasound could stimulate vestibular receptors, citing work by Todd in which the ear's sensitivity was measured in response to mechanical low-frequency stimulation applied by bone conduction. Leventhall fails to make clear that there are no *studies* reporting either vestibular responses, or the absence of vestibular responses, to acoustically-delivered infrasound. This means that for all his strong assertions, Leventhall cannot refer to any study conclusively demonstrating that vestibular receptors of the ear do *not* respond to infrasound. Numerous studies have reported measurements of saccular and utricular responses to audible sound. Indeed, such measurements are the basis of clinical tests of saccular and utricular function through the VEMP (vestibular-evoked myogenic potentials). Some of these studies have shown that sensitivity to acoustic stimulation initially declines as frequency is lowered. On the other hand, *in vitro* experiments demonstrate that vestibular hair cells are maximally sensitive to infrasonic frequencies (~1 – 10 Hz). Thus, sensitivity to acoustic stimulation may increase as stimulus frequency is lowered into the infrasonic range. Direct *in vivo* vestibular excitation therefore remains a possibility until it has been shown that the saccule and other vestibular receptors specifically do not respond to this stimulation.

Low-frequency tone-induced endolymph hydrops, as discussed above, could increase the amount of saccular stimulation by acoustic input. Hydrops causes the compliant saccular membrane to expand, in many cases to the point where it directly contacts the stapes footplate. This was the basis of the now superseded "tack" procedure for Ménière's disease, in which a sharp prosthesis was implanted in the stapes footplate to perforate the enlarging saccule (Schuknecht et al., 1970). When the saccule is enlarged, vibrations will be applied to endolymph, not perilymph, potentially making acoustic stimulation of the receptor more effective. There may also be certain clinical groups whose vestibular systems are hypersensitive to very low-frequency sound and infrasound stimulation. For example, it is known that patients with superior canal dehiscence syndrome are made dizzy by acoustic stimulation. Subclinical groups with mild or incomplete dehiscence could exist in which vestibular organs are more sensitive to low frequency sounds than the general population.

“For years, they have sheltered behind the mantra, now shown to be false, that has been presented repeatedly in many forms such as ‘What you can’t hear, can’t affect you.’ ”

6. Potential Protective Therapy Against Infrasound

A commonly-used clinical treatment could potentially solve the problem of clinical sensitivity to infrasound. Tympanostomy tubes are small rubber “grommets” placed in a myringotomy (small incision) in the tympanic membrane (eardrum) to keep the perforation open. They are routinely used in children to treat middle ear disease and have been used successfully to treat cases of Ménière’s disease. Placement of tympanostomy tubes is a straightforward office procedure. Although tympanostomy tubes have negligible influence on hearing in speech frequencies, they drastically attenuate sensitivity to low frequency sounds (Voss et al., 2001) by allowing pressure to equilibrate between the ear canal and the middle ear. The effective level of infrasound reaching the inner ear could be reduced by 40 dB or more by this treatment. Tympanostomy tubes are not permanent but typically extrude themselves after a period of months, or can be removed by the physician. No one has ever evaluated whether tympanostomy tubes alleviate the symptoms of those living near wind turbines. From the patient’s perspective, this may be preferable to moving out of their homes or using medical treatments for vertigo, nausea, and/or sleep disturbance. The results of such treatment, whether positive, negative, would likely have considerable scientific influence on the wind turbine noise debate.

Conclusions and Concerns

We have described multiple ways in which infrasound and low-frequency sounds could affect the ear and give rise to the symptoms that some people living near wind turbines report. If, in time, the symptoms of those living near the turbines are demonstrated to have a physiological basis, it will become apparent that the years of assertions from the wind industry’s acousticians that “what you can’t hear can’t affect you” or that symptoms are psychosomatic or a nocebo effect was a great injustice. The current highly-polarized situation has arisen because our understanding of the consequences of long-term infrasound stimulation remains at a very primitive level. Based on well-established principles of the physiology of the ear and how it responds to very low-frequency sounds, there is ample justification to take this problem more seriously than it has been to date. There are many important scientific issues that can only be resolved through careful and objective research. Although infrasound generation in the laboratory is technically difficult, some research groups are already in the process of designing the required equipment to perform controlled experiments in humans.

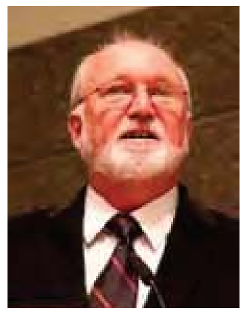
One area of concern is the role that some acousticians and societies of acousticians have played. The primary role of acousticians should be to protect and serve society from negative influences of noise exposure. In the case of wind turbine noise, it appears that many have been failing in that role. For years, they have sheltered behind the mantra, now shown to be false, that has been presented repeatedly in many forms such as “What you can’t hear, can’t affect you.”; “If you cannot hear a sound you cannot perceive it in other ways and it does not affect you.”; “Infrasound from wind turbines is below the audible threshold and of no consequence.”; “Infrasound is negligible from this type of turbine.”; “I can state categorically that there is no significant infrasound from current designs of wind turbines.” All of these statements assume that hearing, derived from low-frequency-insensitive IHC responses, is the only mechanism by which low frequency sound can affect the body. We know this assumption is false and blame its origin on a lack of detailed understanding of the physiology of the ear.

Another concern that must be dealt with is the development of wind turbine noise measurements that have clinical relevance. The use of A-weighting must be reassessed as it is based on insensitive, IHC-mediated hearing and grossly misrepresents inner ear stimulation generated by the noise. In the scientific domain, A-weighting sound measurements would be unacceptable when many elements of the ear exhibit a higher sensitivity than hearing. The wind industry should be held to the same high standards. Full-spectrum monitoring, which has been adopted in some reports, is essential.

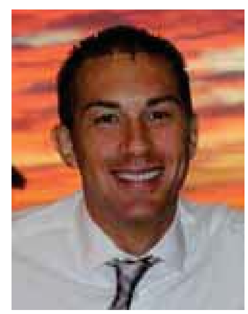
In the coming years, as we experiment to better understand the effects of prolonged low-frequency sound on humans, it will be possible to reassess the roles played by acousticians and professional groups who partner with the wind industry. Given the present evidence, it seems risky at best to continue the current gamble that infrasound stimulation of the ear stays confined to the ear and has no other effects on the body. For this to be true, all the mechanisms we have outlined (low-frequency-induced amplitude modulation, low frequency sound-induced endolymph volume changes, infrasound stimulation of type II afferent nerves, infrasound exacerbation of noise-induced damage and direct infrasound stimulation of vestibular organs) would have to be insignificant. We know this is highly unlikely and we anticipate novel findings in the coming years that will influence the debate.

From our perspective, based on our knowledge of the physiology of the ear, we agree with the insight of Nancy Timmerman that the time has come to "acknowledge the problem and work to eliminate it".

Biosketches



Alec N. Salt is Professor of Otolaryngology at Washington University. He is a long-term member of the Acoustical Society of America, the Association for Research in Otolaryngology, and the American Otological Society. His research covers broad aspects of system-level cochlear physiology, with a major focus on the inner ear fluids, drug delivery to the inner ear, and low-frequency sound effects on the ear.



Jeffery T. Lichtenhan is Assistant Professor of Otolaryngology at Washington University in St. Louis. He recently completed his postdoctoral fellowship in the Eaton-Peabody Laboratory of Auditory Physiology at Harvard Medical School. His research addresses questions on the mechanics of hearing to low-frequency acoustic sound, and the auditory efferent system. Ultimately, his work aims to improve the differential diagnostics of sensorineural hearing loss.

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EXHIBIT 7

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Martti Warpenius
Chairman AAAC

September 18, 2013

Mr Warpenius:

I am stunned that someone who professes to be an expert in acoustics could state something so misleading as “People themselves generate infrasound through things like their own heartbeat, through breathing and these levels of infrasound can be substantially higher than an external noise source.”

Stimulation of the ear occurs not directly by pressure (which is why deep sea divers can still hear) but by induced motions of the inner ear fluids, which in turn move sensory tissues and motion-sensitive cells.

What you fail to understand is that when low frequency and infrasound enters the ear via the stapes, it causes fluid movements throughout the entire ear between the stapes in the vestibule, through scala vestibuli and scala tympani to the compliant round window membrane at the base of scala tympani. It is these fluid movements that drive sensory tissue movements and cause stimulation.

In contrast, pressure fluctuations generated by the body, such as by heartbeat and respiration, enter the ear via the cochlear aqueduct, not through the stapes. The cochlear aqueduct enters the ear adjacent to the round window membrane in the very basal part of scala tympani, so the fluid flows are localized in this tiny region of the ear. As the rest of the ear is bounded by a bony shell which is not compliant, fluid flows in the rest of the ear are substantially lower so that displacements of sensory tissues are negligible. Infrasound generated by the body, because it enters through the aqueduct, therefore does not cause stimulation of the ear.

If you don't understand the anatomy of the ear or this brief explanation, please refer to our paper, Salt & Hullar, Hearing Research 2010; 268: 12; Figure 2.

Experimentally, we know that when infrasonic stimuli are applied to the ear acoustically, via the ear canal and stapes, they generate large electrical responses (Salt et al. J Acoust Soc Am. 2013 133:1561). Yet the sizeable pressures (measurable within the cochlea in mmHg) associated with heartbeat and respiration do not generate significant electrical responses.

I think the time has come when engineers who apparently know little about the physiology of the ear should not be making pseudo-authoritative statements about physiological and clinical aspects of low frequency and infrasound stimulation. Your comments not only fail in their stated goal to "clear up any confusion over the health impact of wind farms", they are simply false and imply that infrasound from external sources such as wind turbines has negligible consequences to people, when we know that is not true.

It is appalling that rather than trying to find the scientific basis and seek solutions to the problem of wind turbine infrasound, the Chairman of the AAAC is peddling misinformation in an attempt to misdirect those who trust their guidance.

In my view, your statements are so misleading they need to be retracted.

Sincerely,

Alec N Salt

Alec N Salt
Professor of Otolaryngology

EXHIBIT 8

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Infrasound From Wind Turbines Could Affect Humans

Alec N. Salt[1] and James A. Kaltenbach[2]

Abstract

Wind turbines generate low-frequency sounds that affect the ear. The ear is superficially similar to a microphone, converting mechanical sound waves into electrical signals, but does this by complex physiologic processes. Serious misconceptions about low-frequency sound and the ear have resulted from a failure to consider in detail how the ear works. Although the cells that provide hearing are insensitive to infrasound, other sensory cells in the ear are much more sensitive, which can be demonstrated by electrical recordings. Responses to infrasound reach the brain through pathways that do not involve conscious hearing but instead may produce sensations of fullness, pressure or tinnitus, or have no sensation. Activation of subconscious pathways by infrasound could disturb sleep. Based on our current knowledge of how the ear works, it is quite possible that low-frequency sounds at the levels generated by wind turbines could affect those living nearby.

Keywords

cochlea, hair cells, A-weighting, wind turbine, Type II auditory afferent fibers

Wind Turbines Generate Infrasound

The sounds generated by wind turbines vary widely, depending on many factors such as the design, size, rotor speed, generator loading, and different environmental conditions such as wind speed and turbulence (e.g., Jakobsen, 2005). Under some conditions, such as with a low wind speed and low generator loading, the sounds generated appear to be benign and are difficult to detect above other environmental sounds (Sonus, 2010).

But in many situations, the sound can contain a substantial low-frequency infrasound component. One study (Van den Berg, 2006) reported wind turbine sounds measured in front of a home 750 m from the nearest turbine of the Rhede wind farm consisting of Enercon E-66 1.8 MW turbines, 98 m hub height, and 35 m blade length. A second study (Jung & Cheung, 2008) reported sounds measured 148 to 296 m from a 1.5 MW turbine, 62 m hub height, 36 m blade length. In both these studies, which are among the few publications that report full-spectrum sound measurements of wind turbines, the sound spectrum was dominated by frequencies below 10 Hz, with levels of over 90 dB SPL near 1 Hz.

The infrasound component of wind turbine noise is demonstrated in recordings of the sound in a home with GE 1.5 MW wind turbines 1,500 ft downwind as shown in Figure 1. This 20-second recording was made with a microphone capable of recording low-frequency components. The sound level over the recording period, from which this excerpt was taken, varied from 28 to 43 dBA. The audible and inaudible (infrasound) components of the sound are demonstrated by filtering the waveform above 20 Hz (left) or below 20 Hz (right). In the audible, high-pass filtered waveform, the periodic "swoosh" of the blade is apparent to a varying degree with time. It is apparent from the low-pass filtered waveform that the largest peaks in the original recording represent inaudible infrasound. Even though the amplitude of the infrasound waveform is substantially larger than that of the audible component, this waveform is inaudible when played by a computer's sound system. This is because conventional speakers are not capable of generating such low frequencies and even if they could, those frequencies are typically inaudible to all but the most sensitive unless played at very high levels. It was also notable in the recordings that the periods of high infrasound level do not coincide with those times when the audible component is high.

This shows that it is impossible to judge the level of infrasound present based on the audible component of the sound. Just because the audible component is loud does not mean that high levels of infrasound are present. These measurements show that wind turbine sounds recorded inside a home can contain a prominent infrasound component.

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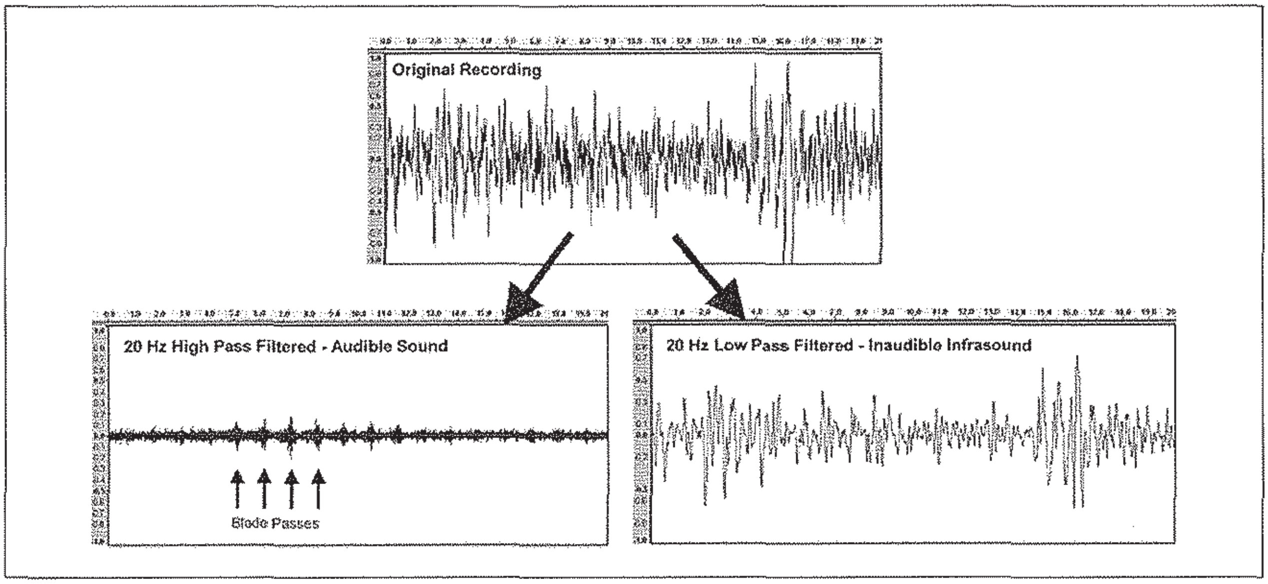

Figure 1. *Upper Panel:* Full-spectrum recording of sound from a wind turbine recorded for 20 seconds in a home with the wind turbine 1,500 ft downwind (digital recording kindly provided by Richard James). *Lower Left Panel:* Result of high-pass filtering the waveform at 20 Hz, showing the sound that is heard, including the sounds of blade passes. *Lower Right Panel:* Result of low-pass filtering the waveform at 20 Hz, showing the infrasound component of the sound

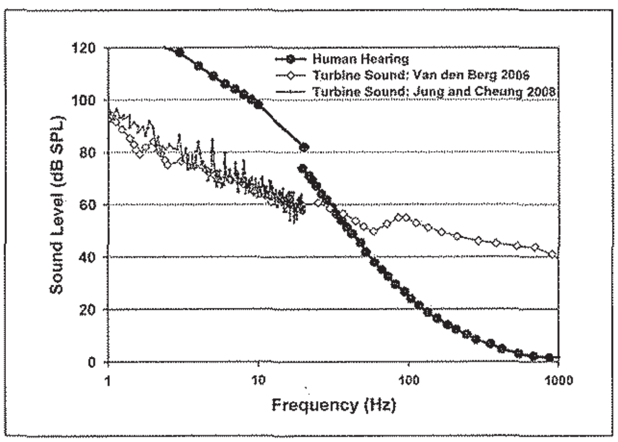

Figure 2. Wide band spectra of wind turbine sounds (Jung & Cheung, 2008; Van den Berg, 2006) compared with the sensitivity of human hearing (International Organization for Standardization, 2003, above 20 Hz; Møller & Pederson, 2004, below 20 Hz). The levels of sounds above 30 Hz are above the audibility curve and would be heard. Below 30 Hz, levels are below the audibility curve so these components would not be heard

Wind Turbine Infrasound Is Typically Inaudible

Hearing is very insensitive to low-frequency sounds, including those generated by wind turbines. Figure 2 shows examples of wind turbine sound spectra compared with the sensitivity of human hearing. In this example, the turbine sound components above approximately 30 Hz are above threshold and therefore audible. The sounds below 30 Hz, even though they are of higher level, are below the threshold of audibility and therefore may not be heard. Based on this comparison, for years it has been assumed that the infrasound from wind turbines is not significant to humans. Leventhall (2006) concluded that "infrasound from wind turbines is below the audible threshold and of no consequence." (p.34) Leventhall (2007) further stated that "if you cannot hear a sound you cannot perceive it in other ways and it does not affect you." (p.135)

Renewable UK (2011), the website of the British Wind Energy Association, quotes Dr. Leventhall as stating, "I can state quite categorically that there is no significant infrasound from current designs of wind turbines." Thus, the fact that hearing is insensitive to infrasound is used to exclude the possibility that the infrasound can have any influence on humans. This has been known for many years in the form of the statement, "What you can't hear can't affect you." The problem with this concept is that the sensitivity of "hearing" is assumed to equate with sensitivity of "the ear." So if you cannot hear a sound then it is assumed that the sound is insufficient to stimulate the ear. Our present knowledge of the physiology of the ear suggests that this logic is incorrect.

The Ear Is Sensitive to Wind Turbine Infrasound

The sensory cells responsible for hearing are contained in a structure in the cochlea (the auditory portion of the inner ear) called the organ of Corti. This organ runs the entire length of the cochlear spiral and contains two types of sensory cells, which have completely different properties. There is one row

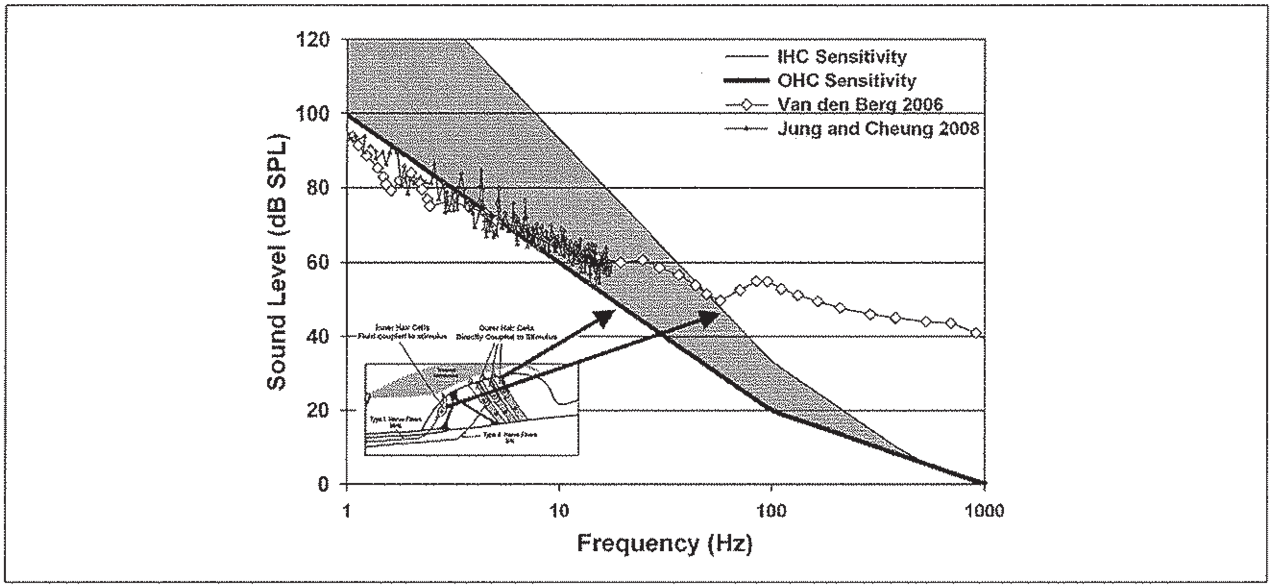

Figure 3. The thin line shows the estimated sensitivity of inner hair cells (IHC) as a function of frequency, which is comparable with the human audibility curve shown in Figure 2 and which is consistent with hearing being mediated by the IHC (based on Cheatham & Dallos, 2001). The thick line shows the estimated sensitivity of the outer hair cells (OHC), which are substantially more sensitive than the IHC. Sound components of the overlaid wind turbine spectra within the shaded region (approximately 5 to 50 Hz) are too low to stimulate the IHC and cannot therefore be heard but are of sufficient level to stimulate the OHC. The inset shows a cross section of the sensory organ of the cochlea (the organ of Corti) showing the locations of the IHC and OHC

of sensory inner hair cells (IHC) and three rows of outer hair cells (OHC) as shown schematically in the inset to Figure 3. For both IHC and OHC, sound-induced deflections of the cell's sensory hairs provide stimulation and elicit electrical responses. Each IHC is innervated by multiple nerve fibers that transmit information to the brain, and it is widely accepted that hearing occurs through the IHC. The rapidly declining sensitivity of hearing at lower frequencies (Figure 2) is accounted for by three processes that selectively reduce low-frequency sensitivity (Cheatham & Dallos, 2001), specifically the properties of middle ear mechanics, from pressure shunting through the cochlear helicotrema and from "fluid coupling" of the inner hair cell stereocilia to the stimulus (reviewed in detail by Salt & Hullar, 2010).

The combined effect of these processes, quantified by Cheatham and Dallos (2001), are shown as the "IHC sensitivity" curve in Figure 3. The last component attenuating low frequencies, the so-called fluid coupling of input, arises because the sensory hairs of the IHC do not contact the overlying gelatinous tectorial membrane but are located in the fluid space below the membrane.

As a result, measurements from the IHC show that they do not respond to sound-induced displacements of the structure but instead their amplitude and phase characteristics are consistent with them responding to the velocity of the stimulus. As stimulus frequency is lowered, the longer cycles result in lower stimulus velocity, so the effective stimulus falls by 6 dB/octave. This accounts for the known insensitivity of the IHC to low-frequency stimuli. For low frequencies, the calculated sensitivity of IHC (Figure 3) compares well with measures of hearing sensitivity (Figure 2), supporting the view that hearing is mediated by the IHC.

The problem, however, arises from the more numerous OHC of the sensory organ of Corti of the ear. Anatomic studies show that the sensory hairs of the OHC are embedded in the overlying tectorial membrane, and electrical measurements from these cells show their responses depend on the displacement rather than the velocity of the structure. As a result, their responses do not decline to the same degree as IHC as frequency is lowered.

Their calculated sensitivity is shown as the "OHC sensitivity" curve in Figure 3. It is important to note that the difference between IHC and OHC responses has nothing to do with frequency-dependent effects of the middle ear or of the helicotrema (the other two of the three components mentioned above). For example, any attenuation of low-frequency stimuli provided by the helicotrema will equally affect both the IHC and the OHC. So the difference in sensitivity shown in Figure 3 arises purely from the difference in how the sensory hairs of the IHC and OHC are coupled to the overlying tectorial membrane.

The important consequence of this physiological difference between the IHC and the OHC is that the OHC are stimulated at much lower levels than the IHC. In Figure 3, the portion of the wind turbine sound spectrum within the shaded region represents frequencies and levels that are too low to be heard, but which are sufficient to stimulate the OHC of the ear.

This is not confined to infrasonic frequencies (below 20 Hz), but in this example includes sounds over the range from 5 to 50 Hz. It is apparent that the concept that "sounds you can't hear cannot affect you" cannot be correct because it does not recognize these well-documented physiologic properties of the sensory cells of the inner ear.

Stimulation of OHC at inaudible, low levels can have potentially numerous consequences. In animals, cochlear microphonics demonstrating the responses of the OHC can be recorded to infrasonic frequencies (5 Hz) at levels as low as 40 dB SPL (Salt & Lichtenhan, in press). The OHCs are innervated by Type II nerve fibers that constitute 5% to 10% of the auditory nerve fibers, which connect the hair cells to the brainstem. The other 90% to 95% come from the IHCs. Both Type I (from IHC) and Type II (from OHC) nerve fibers terminate in the cochlear nucleus of the brainstem, but the anatomical connections of the two systems increasingly appear to be quite different. Type I fibers terminate on the main output neurons of the cochlear nucleus. For example, in the dorsal part of the cochlear nucleus, Type I fibers connect with fusiform cells, which directly process information received from the ear and then deliver it to higher levels of the auditory pathway. In contrast, Type II fibers terminate in the granule cell regions of the cochlear nucleus (Brown, Berglund, Kiang, & Ryugo, 1988). Some granule cells receive direct input from Type II fibers (Berglund & Brown, 1994). This is potentially significant because the granule cells provide a major source of input to nearby cells, whose function is inhibitory to the fusiform cells that are processing heard sounds. If Type II fibers excite granule cells, their ultimate effect would be to diminish responses of fusiform cells to sound. Evidence is mounting that loss of or even just overstimulation of OHCs may lead to major disturbances in the balance of excitatory and inhibitory influences in the dorsal cochlear nucleus. One product of this disturbance is the emergence of hyperactivity, which is widely believed to contribute to the perception of phantom sounds or tinnitus (Kaltenbach et al., 2002; Kaltenbach & Godfrey, 2008). The granule cell system also connects to numerous auditory and nonauditory centers of the brain (Shore, 2005). Some of these centers are directly involved in audition, but others serve functions as diverse as attentional control, arousal, startle, the sense of balance, and the monitoring of head and ear position (Godfrey et al., 1997).

Functions that have been attributed to the dorsal cochlear nucleus thus include sound localization, cancellation of self-generated noise, orienting the head and ears to sound sources, and attentional gating (Kaltenbach, 2006; Oertel & Young, 2004). Thus, any input from OHCs to the circuitry of the dorsal cochlear nucleus could influence functions at several levels.

A-Weighted Wind Turbine Sound Measurements

Measurements of sound levels generated by wind turbines presented by the wind industry are almost exclusively A-weighted and expressed as dBA. When measured in this manner, the sound levels near turbines are typically in the range of 30 to 50 dBA, making wind turbine sounds,

> about the same level as noise from a flowing stream about 50-100 meters away or the noise of leaves rustling in a gentle breeze. This is similar to the sound level inside a typical living room with a gas fire switched on, or the reading room of a library or in an unoccupied, quiet, air-conditioned office. (Renewable UK, 2011)

On the basis of such measurements, we would expect wind turbines to be very quiet machines that would be unlikely to disturb anyone to a significant degree. In contrast, the human perception of wind turbine noise is considerably different. Pedersen and Persson-Waye (2004) reported that for many other types of noise (road traffic, aircraft, railway), the level required to cause annoyance in 30% of people was over 70 dBA, whereas wind turbine noise caused annoyance of 30% of people at a far lower level, at around 40 dBA. This major discrepancy is probably a consequence of A-weighting the wind turbine sound measurements, thereby excluding the low-frequency components that contribute to annoyance. A-weighting corrects sound measurements according to human hearing sensitivity (based on the 40 phon sensitivity curve). The result is that low-frequency sound components are dramatically deemphasized in the measurement, based on the rationale that these components are less easily heard by humans. An example showing the effect of A-weighting the turbine sound spectrum data of Van den Berg (2006) is shown in Figure 4. The low-frequency components of the original spectrum, which resulted in a peak level of 93 dB SPL at 1 Hz, are removed by A-weighting, leaving a spectrum with a peak level of 42 dBA near 1 kHz. A-weighting is perfectly acceptable if hearing the sound is the important factor. A problem arises though when A-weighted measurements or spectra are used to assess whether the wind turbine sound affects the ear. We have shown above that some components of the inner ear, specifically the OHC, are far more sensitive to low-frequency sounds than is hearing. Therefore, A-weighted sounds do not give a valid representation of whether wind turbine noise affects the ear or other aspects of human physiology mediated by the OHC and unrelated to hearing. From Figure 3, we know that sound frequencies down to 3 to 4 Hz may be stimulating the OHC, yet the A-weighted spectrum in Figure 4 cuts off all components below approximately 14 Hz. For this reason, the determination of whether wind turbine sounds affect people simply cannot be made based on A-weighted sound measurements. A-weighted measurements are inappropriate for this purpose and give a misleading representation of whether the sound affects the ear.

Alternatives to A-weighting are the use of full-spectrum (unweighted), C-weighted, or G-weighted measurements. G-weighted measurements use a weighting curve based on the human audibility curve below 20 Hz and a steep cutoff above 20 Hz so that the normal audible range of frequencies is deemphasized. Although the shape of this function is arbitrary

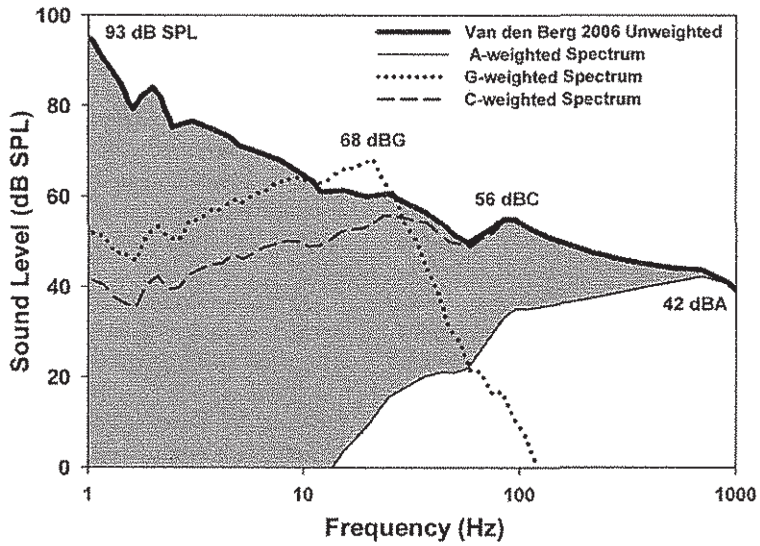

Figure 4. Low-frequency components of wind turbine sound spectrum (below 1 kHz) before and after A-weighting. The original spectrum was taken from Van den Berg (2006). The shaded area represents the degree of alteration of the spectrum by A-weighting. A weighting (i.e., adjusting the spectrum according to the sensitivity of human hearing) has the effect of ignoring the fact that low-frequency sounds can stimulate the OHC at levels that are not heard. Representing this sound as 42 dBA, based on the peak of the spectrum, ignores the possibility that low-frequency components down to frequencies as low as 5 Hz (from Figure 3) are stimulating the OHC. Also shown are the spectra after G-weighting (dotted) and C-weighting (dashed) for comparison

when hearing is not the primary issue, it does give a measure of the infrasound content of the sound that is independent of higher frequency, audible components, as shown in Figure 4. By applying the function to the normal human hearing sensitivity curve, it can be shown that sounds of approximately 95 dBG will be heard by humans, which agrees with observations by Van den Berg (2006). Similarly, by G-weighting the OHC sensitivity function in Figure 3, it can be estimated that sound levels of 60 dBG will stimulate the OHC of the human ear. In a survey of infrasound levels produced by wind turbines measured in dBG (Jakobsen, 2005), upwind turbines typically generated infrasound of 60 to 70 dBG, although levels above and below this range were observed in this and other studies. From Jakobsen's G-weighted measurements, we conclude that the level of infrasound produced by wind turbines is of too low a level to be heard, but in most cases is sufficient to cause stimulation of the OHC of the human ear. C-weighting also provides more representation of low-frequency sound components but still arbitrarily de-emphasizes infrasound components.

Is the Infrasound From Wind Turbines Harmful to Humans Living Nearby?

Our present understanding of inner ear physiology and of the nature of wind turbine sounds demonstrates that low-level infrasound produced by wind turbines is transduced by the OHC of the ear and this information is transmitted to the cochlear nucleus of the brain via Type II afferent fibers. We therefore conclude that dismissive statements such as "there is no significant infrasound from current designs of wind turbines" are undoubtedly false. The fact that infrasound-dependent information, at levels that are not consciously heard, is present at the level of the brainstem provides a scientific basis for the possibility that such sounds can have influence on people. The possibility that low-frequency components of the sound could contribute both to high annoyance levels and possibly to other problems that people report as a result of exposure to wind turbine noise cannot therefore be dismissed out of hand.

Nevertheless, the issue of whether wind turbine sounds can cause harm is more complex. In contrast to other sounds, such as loud sounds, which are harmful and damage the internal structure of the inner ear, there is no evidence that low-level infrasound causes this type of direct damage to the ear. So infrasound from wind turbines is unlikely to be harmful in the same way as high-level audible sounds.

The critical issue is that if the sound is detected, then can it have other detrimental effects on a person to a degree that constitutes harm? A major complicating factor in considering this issue is the typical exposure duration. Individuals living near wind turbines may be exposed to the turbine's sounds for prolonged periods, 24 hours a day, 7 days a week for weeks, possibly extending to years, although the sound level will vary over time with varying wind conditions. Although there have been many studies of infrasound on humans, these have typically involved higher levels for limited periods (typically of up to 24 hours). In a search of the literature, no studies were found that have come close to replicating the long-term exposures to low-level infrasound experienced by those living near wind turbines. So, to date, there are no published studies showing that such prolonged exposures do not harm humans. On the other hand, there are now numerous reports (e.g., Pierpont, 2009; Punch, James, & Pabst, 2010), discussed extensively in this journal, that are highly suggestive that individuals living near wind turbines are made ill, with a plethora of symptoms that commonly include chronic sleep disturbance. The fact that such reports are being dismissed on the grounds that the level of infrasound produced by wind turbines is at too low a level to be heard appears to totally ignore the known physiology of the ear. Pathways from the OHC to the brain exist by which infrasound that cannot be heard could influence function. So, in contrast, from our perspective, there is ample evidence to support the view that infrasound could affect people, and which justifies the need for more detailed scientific studies of the problem. Thus, it is possible that people's health could suffer when turbines are placed too close to their homes and this becomes more probable if sleep is disturbed by the infrasound. Understanding these phenomena may be important to deal with other sources of low-frequency noise and may establish why some individuals are more sensitive than others. A better understanding may also allow effective procedures to be implemented to mitigate the problem.

We can conclude that based on well-documented knowledge of the physiology of the ear and its connections to the brain, it is scientifically possible that infrasound from wind turbines could affect people living nearby.

Declaration of Conflicting Interests

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Bios

Alec N. Salt received his PhD from the University of Birmingham, UK, in 1977 and has been actively involved in research into the physiology of the ear for over 35 years.

James A. Kaltenbach received his PhD from the University of Pennsylvania in 1984. He specializes in the neurobiology of hearing disorders and is currently the Director of Otology Research at the Cleveland Clinic.

EXHIBIT 9

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Effects of industrial wind turbine noise on sleep and health

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Abstract

Industrial wind turbines (IWTs) are a new source of noise in previously quiet rural environments. Environmental noise is a public health concern, of which sleep disruption is a major factor. To compare sleep and general health outcomes between participants living close to IWTs and those living further away from them, participants living between 375 and 1400 m (n = 38) and 3.3 and 6.6 km (n = 41) from IWTs were enrolled in a stratified cross-sectional study involving two rural sites. Validated questionnaires were used to collect information on sleep quality (Pittsburgh Sleep Quality Index — PSQI), daytime sleepiness (Epworth Sleepiness Score — ESS), and general health (SF36v2), together with psychiatric disorders, attitude, and demographics. Descriptive and multivariate analyses were performed to investigate the effect of the main exposure variable of interest (distance to the nearest IWT) on various health outcome measures. Participants living within 1.4 km of an IWT had worse sleep, were sleepier during the day, and had worse SF36 Mental Component Scores compared to those living further than 1.4 km away. Significant dose-response relationships between PSQI, ESS, SF36 Mental Component Score, and log-distance to the nearest IWT were identified after controlling for gender, age, and household clustering. The adverse event reports of sleep disturbance and ill health by those living close to IWTs are supported.

Keywords: *Health, industrial wind turbines, noise, sleep*

Introduction

Environmental noise is emerging as one of the major public health concerns of the twenty-first century.[1] The drive to 'renewable', low-carbon energy sources, has resulted in Industrial Wind Turbines (IWTs) being sited closer to homes in traditionally quiet rural areas to reduce transmission losses and costs. Increasing numbers of complaints about sleep disturbance and adverse health effects have been documented,[2-4] while industry and government reviews have argued that the effects are trivial and that current guidance is adequate to protect the residents.[5,6] We undertook an epidemiological study to investigate the relationship between the reported adverse health effects and IWTs among residents of two rural communities.

Methods

General study design

This investigation is a stratified cross-sectional study involving two sites: Mars Hill and Vinalhaven, Maine, USA. A questionnaire was offered to all residents meeting the participant-inclusion criteria and living within 1.5 km of an industrial wind turbine (IWT) and to a random sample of residents, meeting participant inclusion criteria, living 3 to 7 km from an IWT between March and July of 2010. The protocol was reviewed and approved by Institutional Review Board Services, of Aurora, Ontario, Canada.

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Questionnaire development

Adverse event reports were reviewed, together with the results of a smaller pilot survey of Mars Hill residents. A questionnaire was developed, which comprised of validated instruments relating to mental and physical health (SF-36v2)[7] and sleep disturbance ((Pittsburgh Sleep Quality Index (PSQI)[8] and the Epworth Sleepiness Scale (ESS)[9]). In addition, participants were asked before-and-after IWT questions about sleep quality and insomnia, attitude toward IWTs, and psychiatric disorders. A PSQI score > 5 was taken to indicate poor sleep and an ESS score > 10 was taken to indicate clinically relevant daytime sleepiness.[1-4] Responses to functional and attitudinal questions were graded on a five-point Likert scale with 1 representing the least effect and 5 the greatest. The questionnaire is available on request.

Study sites and participant selection

The Mars Hill site is a linear arrangement of 28 General Electric 1.5 megawatt turbines, sited on a ridgeline. The Vinalhaven site is a cluster of three similar turbines sited on a low-lying, tree-covered island. All residents living within 1.5 km of an IWT, at each site, were identified via tax maps, and approached either door-to-door or via telephone and asked to participate in the study (near group). Homes were visited thrice or until contact was made. Those below the age of 18 or with a diagnosed cognitive disorder were excluded. A random sample of households in similar socioeconomic areas, 3 to 7 km away from IWTs at each site, were chosen to participate in the study to allow for comparison (far group). The households were approached sequentially until a similar number of participants were enrolled. A nurse practitioner supervised the distribution and ensured completion of the questionnaires.

Simultaneous collection of sound levels during data collection at the participants' residences was not possible, but measured IWT sound levels at various distances, at both sites, were obtained from publically available sources. At the Mars Hill site, a four quarter study was conducted and data from all four seasons were reported by power outputs at several key measurement points. The measurement points were located on or near residential parcels. The predicted and measured levels at full power were derived from figures in the Sound Level Study, Compilation of Ambient and Quarterly Operations Sound Testing, and the Maine Department of Environmental Protection Order No. L-21635-26-A-N. Measured noise levels versus distance at Vinalhaven were taken over a single day in February 2010, with the turbines operating at less than full power in moderate-to-variable northwest winds aloft (R and R, personal communication, 2011). Table 1 shows the estimated and measured noise levels at locations of varying distances and directions from the turbines at Mars Hill and Vinalhaven.

Data handling and validation

The Principal Investigator (Michael Nissenbaum, MD) did not handle data at any point in the collection or analysis phase. Questionnaire results were coded and entered into a spreadsheet (Microsoft Excel 2007). Each questionnaire generated over 200 data elements. The distance from each participant's residence to the nearest IWT was measured using satellite maps. The SF36-V2 responses were processed using Quality Metric Health Outcomes™ Scoring Software 3.0 to generate Mental (MCS) and Physical (PCS) Component Scores.

Data quality of the SF36-V2 responses was determined using QualityMetric Health Outcomes™ Scoring Software 3.0. All SF36-V2 data quality indicators (completeness, response range, consistency, estimable scale scores, internal consistency, discriminant validity, and reliable scales) exceeded the parameter norms. SF 36-V2 missing values were automatically accommodated by the scoring systems (99.9% questions were completed). No missing values were present for other parameters (ESS, PSQI, psychiatric and attitudinal observations, and demographics).

Table 1: Measured and predicted noise levels at Mars Hill and Vinalhaven

Mars hill			
Distance to nearestturbine (m)[1]	Predicted max. LAeq 1 hr[1]	Measured noise LAeq 1 hr[1]	
		Average	Range
244	51	52	50 – 57
320	48	50	48 – 53
366	47	49	47 – 52
640	42	44	40 – 47
762	41	43	41 – 46
1037	39	41	39 – 45
1799	35	37	32 – 43

Vinalhaven		
Distance to nearest turbine (m)[2]	Measured Noise LAeq[2]	
	Trend Average	Range
152	53	51 – 61
366	46	38 – 49
595	41	39 – 49
869	38	32 – 41
1082	36	34 – 43

[1] Values read or derived from report figures; accuracy + /- 50 m and + /- 1 Db [2] Values obtained with wind turbine noise dominating the acoustical environment, two-minute measurements during moderate-to-variable northwest winds aloft (less than full power)

Statistical analysis

All analyses were performed using SAS 9.22.[10] Descriptive and multivariate analyses were performed to investigate the effect of the main exposure variable of interest (distance to the nearest IWT) on the various outcome measures. Independent variables assessed included the following: Site (Mars Hill, Vinalhaven); Distance to IWT (both as a categorical and continuous variable); Age (continuous variable); Gender (categorical variable). The dependent variables assessed included the following: Summary variables — Epworth Sleepiness Scale (ESS), Pittsburgh Sleep Quality Index (PSQI), SF36-V2 Mental Component Score (MCS), SF36-V2 Physical Component Score (PCS); Before and after parameters — sleep, psychiatric disorders (both self-assessed and diagnosed by a physician), attitude toward IWTs; and Medication use (both over-the-counter and prescription drugs). A P value of < 0.05 was regarded as being statistically significant.

Results

Study participants

Thirty-three and 32 adults were identified as living within 1500 m of the nearest IWT at the Mars Hill (mean 805 m, range 390 – 1400) and Vinalhaven sites (mean 771 m range 375 – 1000), respectively. Twenty-three and 15 adults at the Mars Hill and Vinalhaven sites respectively, completed the questionnaires. Recruitment of participants into the far group continued until there were similar numbers as in the near group, 25 and 16 for Mars Hill and Vinalhaven, respectively [Table 2].

Statistical results

The binomial outcomes were assessed using either the GENMOD procedure with binomial distribution and a logit link; or when cell frequencies were small (< 5), Fisher's Exact Test. When assessing the significance between variables with a simple score outcome (e.g., 1 – 5), the exact Wilcoxon Score (Rank Sums) test was employed using the NPAR1WAY procedure. Continuous outcome variables were assessed using the GENMOD procedure with normal distribution. When using the GENMOD procedure, age, gender, and site were forced into the model as fixed effects. The potential effect of household clustering on statistical significance was accommodated by using the REPEATED statement. Effect of site as an effect modifier was assessed by evaluating the interaction term (Site*Distance).

Participants living near IWTs had worse sleep, as evidenced by significantly greater mean PSQI and ESS scores [Table 3]. More participants in the near group had PSQI > 5 (P = 0.0745) and ESS scores > 10 (P = 0.1313), but the differences did not reach statistical significance. Participants living near IWTs were significantly more likely to report an improvement in sleep quality when sleeping away from home.

Table 2: Demographic data of Mars Hill and Vinalhaven study participants

	Distance (m) from residence to nearest IWT (mean)			
Parameter	375 – 750 (601)	751 – 1400 (964)	3300 – 5000 (4181)	5300 – 6600 (5800)
Sample size	18	20	14	27
Household clusters	11	12	10	23
Mean age	50	57	65	58
Male / Female	10 / 8	12 / 8	7 / 7	11 / 16
Mean time in home[1]	14	21	30	24

[1] Years that study participants lived in the home

The near group had worse mental health as evidenced by significantly higher mean SF36 MCS (P = 0.0021) [Table 3]. There was no statistically significant difference in PCS (P = 0.9881). Nine participants in the near group reported that they had been diagnosed with either depression or anxiety since the start of turbine operations, compared to none in the far group. Nine of the 38 participants in the near group reported that they had been prescribed new psychotropic medications since the start of turbine operations compared with three of 41 in the far group (P = 0.06).

The ESS, PSQI, and SF36 scores were modeled against distance from the nearest IWT (Score = ln (distance) + gender + age + site [controlled for household clustering]), and the results are shown in Figures 1–3. In all cases, there were clear and significant dose-response relationships (P < 0.05), with the effect diminishing with increasing log-distance from IWTs. Log-distance fit the health outcomes better than distance. This was expected given that noise drops off as the log of distance. Measured sound levels were plotted against distance at the two sites on Figures 1-3.

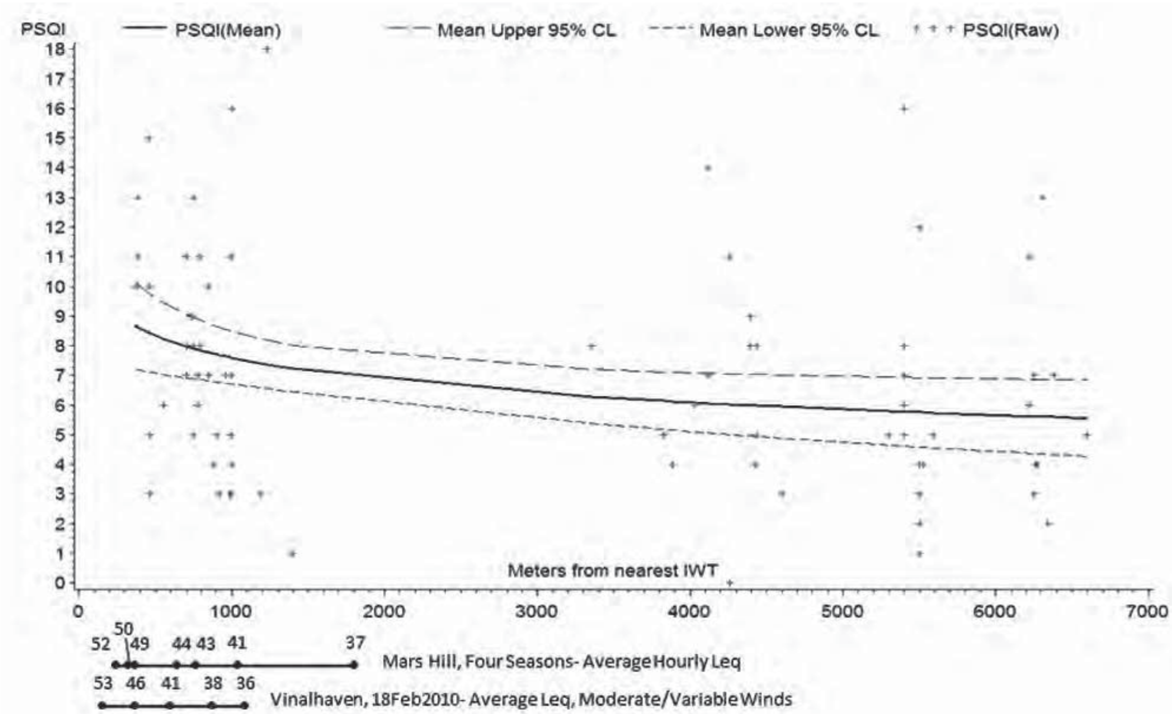

Figure 1: Modeled Pittsburgh Sleep Quality Index (PSQI) versus distance to nearest IWT (mean and 95% confidence limits) Regression equation: PSQI = ln (distance) + sex + age + site [controlled for household clustering]. Ln (distance) *p*-value = 0.0198

Table 3: Sleep and mental health outcomes of the study participants grouped by distance from the nearest IWT

	Distance (m) from residence to nearest IWT (mean)						
Parameter	375-750 (601)	751-1400 (964)	375-1400 (792)	3300-5000 (4181)	5300-6600 (5800)	3000-6600 (5248)	P-Value[1]
Mean PSQI[2]	8.7	7.0	7.8	6.6	5.6	6.0)	0.0461
% PSQI score > 5[3]	77.8	55.0	65.8	57.1	37.0	43.9	0.0745
Mean ESS[4]	7.2	8.4	7.8	6.4	5.3	5.7	0.0322
% with ESS score > 10[5]	16.7	30.0	23.7	14.3	7.4	9.8	0.1313
Mean worsening sleep score post IWTs[6]	3.2	3.1	3.1	1.2	1.4	1.3	< .0001
Improved sleep when away from IWTs	9 / 14	5 / 14	14 / 28	1 / 11	1 / 23	2 / 34	< .0001
% New sleep medications post IWTs	11.1	15.0	13.2	7.1	7.4	7.3	0.4711
New diagnoses of insomnia			2			0	
Mean SF36 MCS	40.7	43.1	42.0	50.7	54.1	52.9	0.0021
% Wishing to move away post IWTs	77.8	70.0	73.7	0.0	0.0	0.0	< .0001

[1] Testing difference of 375 – 1400 m group with 3000 – 6600 m group [2] Pittsburgh Sleep Quality Index [3] PSQI > 5 is considered a 'poor sleeper' [4] Epworth Sleepiness Scale [5] About 10 – 20 percent of the general population has ESS scores > 10 [6] (New sleep problems + Worsening sleep problem)/2; Strongly Agree (5) - Strongly disagree (1)

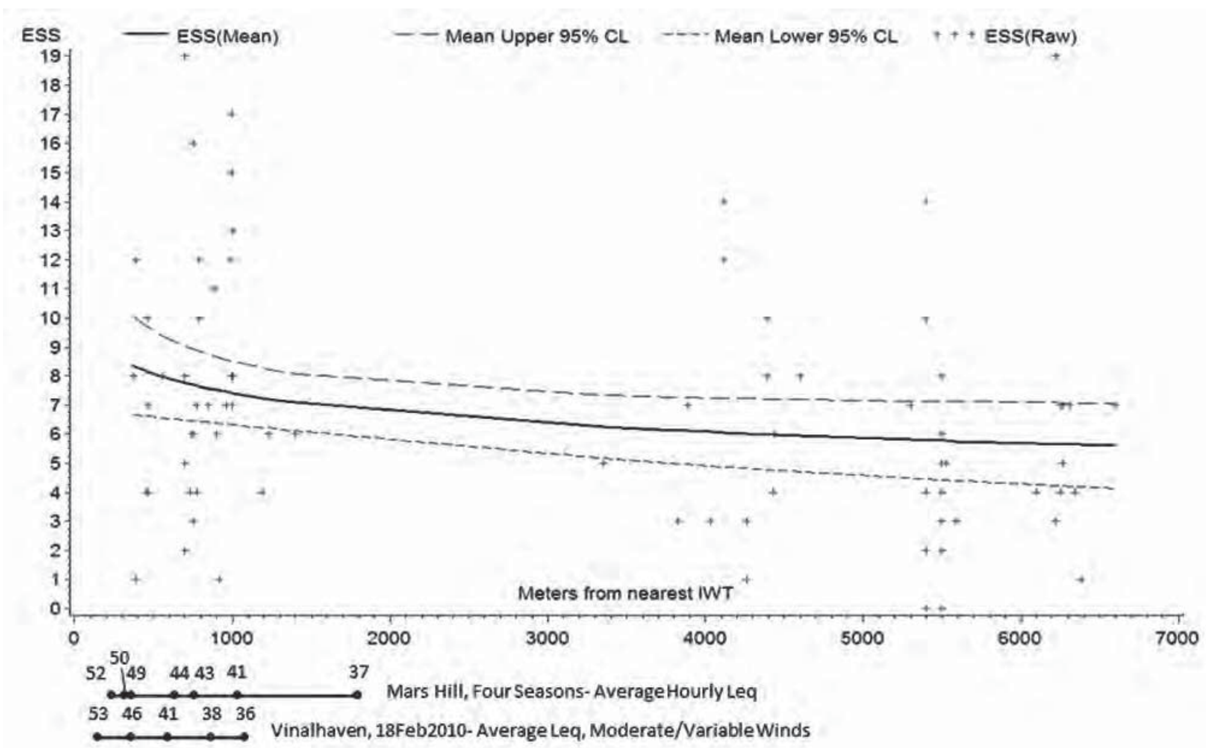

Figure 2: Modeled Epworth Sleepiness Scale (ESS) versus Distance to nearest IWT (mean and 95% confidence limits) Regression equation: ESS = ln (distance) + sex + age + site [controlled for household clustering)]. ln (distance) p-value = 0.0331

There were no statistically significant differences between the near and far groups with respect to age, gender, or duration of occupation. In addition, Site, and Site*Distance were not significant, indicating that the modeled exposure-outcome relationships were similar across both sites.

Discussion

This study supports the conclusions of previous studies, which demonstrate a relationship between proximity to IWTs and the general adverse effect of 'annoyance',[11-13] but differs in demonstrating clear dose-response relationships in important clinical indicators of health including sleep quality, daytime sleepiness, and mental health. The levels of sleep disruption and the daytime consequences of increased sleepiness, together with the impairment of mental health and the dose-response relationships observed in this study (distance from IWT vs. effect) strongly suggest that the noise from IWTs results in similar health impacts as other causes of excessive environmental noise[1].

The degree of effect on sleep and health from IWT noise seems to be greater than that of other sources of

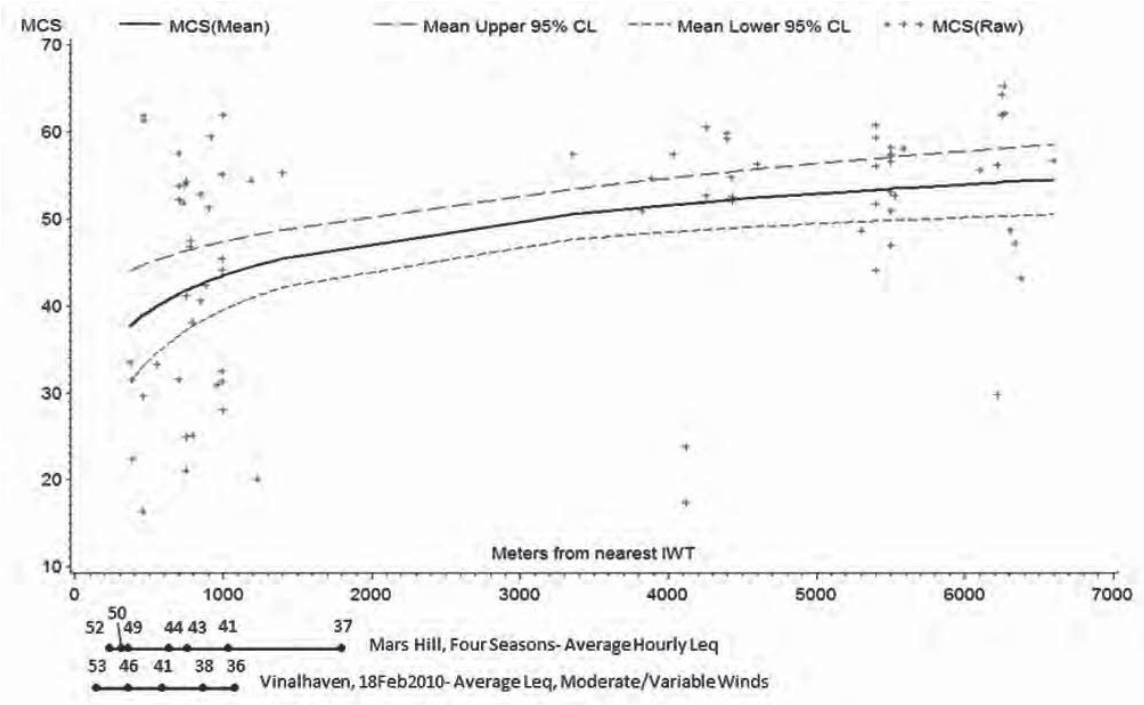

Figure 3: Modeled SF36 Mental Component Score (MCS) versus Distance to nearest IWT (mean and 95% confidence limits) Regression equation: MCS = ln (distance) + sex + age + site [controlled for household clustering]. ln (distance) p-value = 0.0014

environmental noise, such as, road, rail, and aircraft noise. Bray and James have argued that the commonly used noise metric of LAeq (averaged noise level adjusted to human hearing) is not appropriate for IWT noise, which contains relatively high levels of low frequency sound (LFN) and infrasound with impulsive characteristics.[14] This has led to an underestimation of the potential for adverse health effects of IWTs.

Potential biases

Reporting and selection biases in this study, if they existed, may have underestimated the strength of the association between distance to IWTs and health outcomes. Both Mars Hill and Vinalhaven residents gain financially from the wind projects, either through reduced electricity costs and / or increased tax revenues. The fear of reducing property values was also cited as a reason for downplaying the adverse health effects. Conversely, the possibility of legal action could result in symptoms being over stated. It was clear to the respondents that the questionnaire was directed at investigating adverse health effects potentially associated with IWT noise and no distractor questions were included. Nevertheless, given the large differences in reported adverse health effects between participants living within 1400 m and those living beyond 3300 m of an IWT, we do not believe that bias alone could have resulted in the differences demonstrated between the groups. In addition, the finding of strong dose-response relationships with log-distance, together with extensive sub-analyses using survey questions more and less likely to be influenced by bias demonstrating similar results, further support the existence of causative associations.

Visual impact and attitude are known to affect the psychological response to environmental noise.[11,15,16] At both sites, turbines are prominent features of the landscape and were visible to a majority of respondents; at Mars Hill, IWTs are sited along a 200 m high ridge, and Vinalhaven is a flat island. The visual impact on those living closest to turbines was arguably greater than on those living some distance away. Most residents welcomed the installation of IWTs for their proposed financial benefits and their attitudes only changed once they began to operate and the noise and health effects became apparent. Pedersen estimates that, with respect to annoyance, 41% of the observed effects of IWT noise could be attributed to attitude and visual impact.[11] The influence of these factors on other consequences, such as the health effects investigated in this study, remains to be determined. Even as these factors may have contributed to the reported effects, they are clearly not the sole mechanism and health effects are certain.

Mechanisms

A possible mechanism for the observed health effects is an effect on sleep from the noise emitted by IWTs. Industrial wind turbines emit high levels of noise with a major low frequency component. The noise is impulsive in nature and variously described as 'swooshing' or 'thumping'.[12] The character, volume, and frequency of the noise vary with changes in wind speed and direction. Industrial wind turbine noise is more annoying than road, rail, and aircraft noise, for the same sound pressure, presumably due to its impulsive character.[12,15] Pedersen concludes that it is noise that prevents restoration, that those subjected to it are unable to find psychological recovery in their homes because of its intrusive nature.[16] Noise can affect sleep by preventing sleep onset or return to sleep following spontaneous or induced awakening. Clearly, attitude and psychological factors such as noise sensitivity may be important in influencing the ability to fall asleep, but it should be noted that noise sensitivity is, in part, heritable.[17] Noise also affects sleep by inducing arousals, which fragment sleep, reducing its quality and leading to the same consequences as sleep deprivation.[18] There is good evidence that road, rail, and aircraft noise induce arousals and lead to daytime consequences and there is no reason to suppose that IWT noise will not have a similar effect.[19-23] A recent study on the likelihood of different hospital noises that induce an arousal shows a considerable effect of sound character, with impulsive noises being more likely to induce an arousal.[24] It has also been shown that there is individual variability in the likelihood of an arousal in response to noise, which may be predicted from a spindle index, a measure of sleep quality.[25]

ESS assesses daytime sleepiness from the self-assessed propensity to fall asleep in different situations averaged over several weeks.[9] It is widely used in sleep medicine to assess daytime sleepiness, and scores in excess of 10 are deemed to represent clinically relevant excessive daytime sleepiness. If sleep is only disrupted occasionally, the ESS will not be affected, as the sleep deficit can be compensated on other nights. Changes in the ESS score observed in this study imply that sleep has been disrupted to a degree where compensation is not possible in at least some participants. PSQI also examines the sleep quality averaged over a period of weeks, scores in excess of 5 are deemed to represent poor quality sleep.[8] An individual's score will not be significantly affected by occasional disrupted nights, thus confirming the conclusions drawn from the ESS data. It is noteworthy also that significant changes in ESS and PSQI have been observed, despite the scatter in values indicative of the typical levels of impaired sleep found in the general population.[8,9]

Other mechanisms than sleep disruption cannot be excluded as an explanation for the psychological and other changes observed. Low frequency noise, and in particular, impulsive LFN, has been shown to be contributory to the symptoms of 'Sick Building Syndrome,' which has similarities with those reported here.[26,27] Salt has recently proposed a mechanism, whereby, infrasound from IWTs could affect the cochlear and cause many of the symptoms described.[28]

We assessed causality using a well-accepted framework.[29] Although the measured parameters (ESS, PSQI, and SF36) assess the current status, the evidence of the respondents is that the reported changes have followed the commencement of IWT operation. This is supported by the reported preferences of the residents; the great majority of those living within 1.4 km expressed their desire to move away as a result of the start of turbine operations. However, a study of the same population before and after turbine operation will be necessary to confirm our supposition. We believe that there is good evidence that a time sequence has been established. The association between distance to IWT and health outcome is both statistically significant and clinically relevant for the health outcomes assessed, suggesting a specific association between the factors. Given that this is the first study investigating the association between IWTs and a range of health outcomes, the consistency and replication to prove causation is limited. However, this study includes two different study populations living next to two different IWT projects. Despite these differences, the study site was not a significant effect modifier among any of the measured outcomes. In addition, adverse health effects similar to those identified in this study among those living near IWTs, have been documented in a number of case-series studies and surveys.[2-4,30] Finally, causal association can be judged by its coherence with other known facts about the health outcomes and the causal factor under study. The results of this study are consistent with the known effects of other sources of environmental noise on sleep.

The data on measured and estimated noise levels were not adequate to construct a dose-response curve and to determine an external noise level below which sleep disturbance will not occur. However, it is apparent that this value will be less than an average hourly LAeq of 40 dBA, which is the typical night time value permitted under the current guidance in most jurisdictions.

Conclusions

We conclude that the noise emissions of IWTs disturbed the sleep and caused daytime sleepiness and impaired mental health in residents living within 1.4 km of the two IWT installations studied. Industrial wind turbine noise is a further source of environmental noise, with the potential to harm human health. Current regulations seem to be insufficient to adequately protect the human population living close to IWTs. Our research suggests that adverse effects are observed at distances even beyond 1 km. Further research is needed to determine at what distances risks become negligable, as well as to better estimate the portion of the population suffering from adverse effects at a given distance.

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EXHIBIT 10

Attention Deficit Hyperactivity Disorder and Dirty Electricity

To the Editor:

In February 2010, while studying a cancer cluster in teachers at a California elementary school, a fourth-grade teacher complained that her students were hyperactive and unteachable. The classroom levels of high-frequency voltage transients (dirty electricity) in the radio frequencies (RF) between 4 and 100 kHz measured in the outlets of her classroom with a Graham/Stetzer Microsurge meter were very high. Dirty electricity is a term coined by the electrical utilities to describe electrical pollution contaminating the 60 Hz electricity on the electrical grid. A cell phone tower on campus a few feet from this classroom and unshielded fluorescent lights both contributed to the electrical pollution in this room. Cell tower transmitters, like most modern electrical equipment, operate on direct current. The electrical current brought to the tower is alternating current that needs to be changed to direct current. This is done by a switching power supply. These devices interrupt the alternating current and are the likely major source of the dirty electricity in the classroom.

On a Friday afternoon after school, I filtered the 5 outlets in this room with Graham/Stetzer plug-in capacitive filters, reducing the measured dirty electricity in the room wiring from more than 5000 Graham/Stetzer units to less than 50 units. With no change in either the lighting or the cell tower radiation, the teacher reported an immediate dramatic improvement in the behavior of her students in the following week. They were calmer, paid more attention, and were teachable all week except for Wednesday when they spent part of the day in the library.

In his 1973 book, Health and Light,[1] John N. Ott described a 1973 study of 4 first-grade classrooms in a windowless Sarasota, Florida school. Two of the rooms had standard white fluorescent lighting and the other two had full-spectrum fluorescent lighting with a grounded aluminum wire screen to remove the RF radiation produced by fluorescent bulbs and ballasts. Concealed time-lapse cameras recorded student behavior in classrooms for 4 months.[2] In the unshielded rooms, the first graders developed, "... nervous fatigue, irritability, lapses of attention, and hyperactive behavior." "... students could be observed fidgeting to an extreme degree, leaping from their seats, flailing their arms, and paying little attention to their teachers." In the RF-shielded rooms, "Behavior was entirely different. Youngsters were calmer and far more interested in their work."

The Old Order Amish live without electricity. A pediatric group practice in Jasper, Indiana, which cares for more than 800 Amish families has not diagnosed a single child with attention deficit hyperactivity disorder (ADHD).[3] Dozens of cases of childhood ADHD have been "cured" with no further need for drugs by simply changing their electrical environments (Stetzer D, personal communication [www.Stetzerelectric.com]). AQ:A

Before children are treated with drugs for ADHD, the dirty electricity levels in their homes and school environments should first be examined and reduced if needed.

I present the epidemiologic evidence linking dirty electricity to the other diseases of civilization in a recent book.[4,5] AQ:B

Disclosure: The authors declare no conflict of interest. AQ:C

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EXHIBIT 11

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Historical evidence that electrification caused the 20th century epidemic of "diseases of civilization" ☆

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SUMMARY

The slow spread of residential electrification in the US in the first half of the 20th century from urban to rural areas resulted by 1940 in two large populations; urban populations, with nearly complete electrification and rural populations exposed to varying levels of electrification depending on the progress of electrification in their state. It took until 1956 for US farms to reach urban and rural non-farm electrification levels. Both populations were covered by the US vital registration system. US vital statistics tabulations and census records for 1920–1960, and historical US vital statistics documents were examined. Residential electrification data was available in the US census of population for 1930, 1940 and 1950. Crude urban and rural death rates were calculated, and death rates by state were correlated with electrification rates by state for urban and rural areas for 1940 white resident deaths. Urban death rates were much higher than rural rates for cardiovascular diseases, malignant diseases, diabetes and suicide in 1940. Rural death rates were significantly correlated with level of residential electric service by state for most causes examined. I hypothesize that the 20th century epidemic of the so called diseases of civilization including cardiovascular disease, cancer and diabetes and suicide was caused by electrification not by lifestyle. A large proportion of these diseases may therefore be preventable.

Background

In 2001, Ossiander and I [1] presented evidence that the childhood leukemia mortality peak at ages 2–4 which emerged in the US in the 1930s was correlated with the spread of residential electrification in the first half of the 20th century in the US. While doing the childhood leukemia study, I noticed a strong positive correlation between level of residential electrification and the death rate by state due to some adult cancers in 1930 and 1940 vital statistics. At the time, a plausible electrical exposure agent and a method for its delivery within residences was lacking. However, in 2008 I coauthored a study of a cancer cluster in school teachers at a California middle school [2] which indicated that high frequency voltage transients (also known as dirty electricity), were a potent universal carcinogen with cancer risks over 10.0 and significant dose–response for a number of cancers. They have frequencies between 2 and 100 kHz. These findings are supported by a large cancer incidence study in 200,000 California school employees which showed that the same cancers and others were in excess in California teachers statewide [3]. Power frequency magnetic fields (60 Hz) measured at the school were low and not related to cancer incidence, while classroom levels of high frequency voltage transients measured at the electrical outlets in the classrooms accurately predicted a teacher's cancer risk. These fields are potentially present in all wires carrying electricity and are an important component of ground currents returning to substations especially in rural areas. This helped explain the fact that professional and office workers, like the school teachers, have high cancer incidence rates. It also explained why indoor workers had higher malignant melanoma rates, why melanoma occurred on part of the body which never are exposed to sunlight, and why melanoma rates are increasing while the amount of sunshine reaching earth is stable or decreasing due to air pollution. A number of very different types of cancer had elevated risk in the La Quinta school study, in the California school employees study, and in other teacher studies. The only other carcinogenic agent which acts like this is ionizing radiation.

Among the many devices which generate the dirty electricity are compact fluorescent light bulbs, halogen lamps, wireless routers, dimmer switches, and other devices using switching power supplies. Any device which interrupts current flow generates dirty electricity. Arcing, sparking and bad electrical connections can also generate the high frequency voltage transients. Except for the dimmer switches, most of these devices did not exist in the first half of the 20th century. However, early electric generating equipment

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and electric motors used commutators, carbon brushes, and split rings, which would inject high frequency voltage transients into the 60 Hz electricity being generated and distributed.

With a newly recognized electrical exposure agent and a means for its delivery, I decided to examine whether residential electrification in the US in the first half of the last century was related to any other causes of death. Most cancers showed increasing mortality in this period, and many are still increasing in incidence in the developed world.

Thomas Edison began electrifying New York City in 1880, but by 1920, only 34.7% of all US dwelling units and 1.6% of farms had electric service (Table 1). By 1940, 78% of all dwelling units and 32% of farms had electric service [4]. This means that in 1940 about three quarters of the US population lived in electrified residences and one quarter did not. By 1940, the US vital registration system was essentially complete, in that all the 48 contiguous United States were included. Most large US cities were electrified by the turn of the century, and by 1940, over 90% of all the residences in the northeastern states and California were electrified. In 1940 almost all urban residents in the US were exposed to electromagnetic fields (EMFs) in their residences and at work, while rural residents were exposed to varying levels of EMFs, depending on the progress of rural electrification in their states. In 1940, only 28% of residences in Mississippi were electrified, and five other southern states had less than 50% of residences electrified (Table 2). Eleven states, mostly in the northeast had residential electrification rates above 90%. In the highly electrified northeastern states and in California, urban and rural residents could have similar levels of EMF exposure, while in states with low levels of residential electrification, there were potentially great differences in EMF exposure between urban and rural residents. It took the first half of the 20th century for these differences to disappear. I examined US mortality records by urban and rural residence by percent of residences with electric service by state.

Hypothesis

The diseases of civilization or lifestyle diseases include cardiovascular disease, cancer and diabetes and are thought to be caused by changes in diet, exercise habits, and lifestyle which occur as countries industrialize. I think the critical variable which causes the radical changes in mortality accompanying industrialization is electrification. Beginning in 1979, with the work of Wertheimer and Leeper [5], there has been increasing evidence that some facet of electromagnetic field exposure is associated epidemiologically with an increased incidence of leukemia, certain other cancers and non-cancers like Alzheimer's disease, amyotrophic lateral sclerosis, and suicide. With the exception of a small part of the electromagnetic spectrum from infra red through visible light, ultraviolet light and cosmic rays, the rest of the spectrum is man-made and foreign to human evolutionary experience. I suggest that from the time that Thomas Edison started his direct current electrical distribution system in the 1880s in New York City until now, when most of the world is electrified, the electricity carried high frequency voltage transients which caused and continue to cause what are considered to be the normal diseases of civilization. Even today, many of these diseases are absent or have very low incidence in places without electricity.

Table 1
Growth of residential electric service US 1920–1956 percent of dwelling units with electric service.

Year	All		Urban and rural non-farm
	Dwellings	Farm	
1920	34.7	1.6	47.4
1925	53.2	3.9	69.4
1930	68.2	10.4	84.8
1935	68.0	12.6	83.9
1940	78.7	32.6	90.8
1945	85.0	48.0	93.0
1950	94.0	77.7	96.6
1956	98.8	95.9	99.2

Table 2
Percent of residences with electric lighting 1930 and 1940 by state.

Code	State	1930	1940
AL	Alabama	33.9	43.3
AZ	Arizona	68.8	70.5
AR	Arkansas	25.3	32.8
CA	California	93.9	96
CO	Colorado	69.6	77.6
CT	Connecticut	95.3	96.5
DE	Delaware	78.4	81.8
FL	Florida	60.9	66.5
GA	Georgia	35.5	46.6
ID	Idaho	64.5	79.1
IL	Illinois	86.1	89.9
IN	Indiana	74.8	84
IA	Iowa	65.6	76.7
KS	Kansas	62	71.5
KY	Kentucky	44.2	54.2
LA	Louisiana	42.2	48.9
ME	Maine	76.1	80.4
MD	Maryland	81.8	85.9
MA	Massachusetts	97.1	97.6
MI	Michigan	84.8	92.1
MN	Minnesota	65.9	75.8
MS	Mississippi	19.4	28.3
MO	Missouri	65.5	70.6
MT	Montana	58.2	70.7
NE	Nebraska	61	70.5
NV	Nevada	76.2	80.8
NH	New Hampshire	84.9	87
NJ	New Jersey	95.8	96.6
NM	New Mexico	39.8	49.2
NY	New York	94.5	96.4
NC	North Carolina	40.8	54.4
ND	North Dakota	41.6	53.8
OH	Ohio	85.2	90.6
OK	Oklahoma	45.3	55.1
OR	Oregon	79.5	85.8
PA	Pennsylvania	89.5	92.3
RI	Rhode Island	97.3	97.7
SC	South Carolina	34.3	46.2
SD	South Dakota	44.4	56.6
TN	Tennessee	42	50.9
TX	Texas	*	59
UT	Utah	88.4	93.9
T	Vermont	71.9	80.2
VA	Virginia	50.5	60.6
WA	Washington	86.3	90.9
WV	West Virginia	63.4	69.1
WI	Wisconsin	74.5	83.9
WY	Wyoming	60	70.9

*No data.

Evaluation of the hypothesis

To evaluate the hypothesis, I examined mortality in US populations with and without residential electrification. Vital statistics tabulations of deaths [6], US census records for 1920–1970 [7], and historical US documents [8,9] were examined in hard copy or downloaded from the internet. The same state residential electrification data used in the childhood leukemia study [1] was used in this study. Crude death rates were calculated by dividing number of deaths by population at risk, and death rates by state were then correlated with electrification rates by state using downloaded software [10]. Time trends of death rates for selected causes of death by state were examined. Most rates were calculated by state for urban and rural residence for whites only in 1940 deaths, since complete racial data was available by urban/rural residence by state for only 13 of 48 states. Data was available for 48 states in the 1940 mortality tabulations. District of Columbia was excluded because it was primarily an urban population. Excel graphing software [11] and "Create a Graph" [12] software was used.

I had hoped to further test this hypothesis by studying mortality in individual US farms with and without electrification, when the 1930 US census 70 year quarantine expired in 2000. Unfortunately, the 1930 US farm census schedules had been destroyed.

Findings

Rural residential electrification did not reach urban levels until 1956 (Table 1). Table 2 shows the level of residential electrification for each state for 1930 and 1940. In 1930 and 1940 only 9.5% and 13%, respectively, of all generated electricity was used in residences. Most electricity was used in commercial and industrial applications.

Figs. 1–4 were copied and scanned from "Vital statistics rates in the United States 1940–1960", by Robert Grove Ph.D. and Alice M. Henzel. This volume was published in 1968. Fig. 1 shows a gradual decline in the all causes death rate from 1900 to 1960 except for a spike caused by the 1918 influenza pandemic. Death rates due to tuberculosis, typhoid fever, diphtheria, dysentery, influenza and pneumonia and measles all fell sharply in this period, and account for most of the decline in the all causes death rate. Figs. 2–4 show that in the same time period when the all causes death rate was declining, all malignant neoplasms (Fig. 2), cardiovascular diseases (Fig. 3), and diabetes (Fig. 4) all had gradually increasing death rates. In 1900, heart disease and cancer were 4th and 8th in a list of 10 leading causes of death. By 1940 heart disease had risen to first and cancer to second place, and have maintained that position ever since. Table 3 shows that for all major causes of death examined, except motor vehicle accidents, there was a sizable urban excess in 1940 deaths. The authors of the extensive 69 page introduction to the 1930 mortality statistics volume noted that the cancer rates for cities were 58.2% higher than those for rural areas. They speculated that some of this excess might have been due to rural residents dying in urban hospitals. In 1940, deaths by place of residence and occurrence are presented in separate volumes. In 1940 only 2.1% of all deaths occurred to residents of one state dying in another state. Most non-resident deaths were residents of other areas of the same state. Table 4 presents correlation coefficients for the relationship between death rates by urban rural areas of each state and the percent of residences in each state with

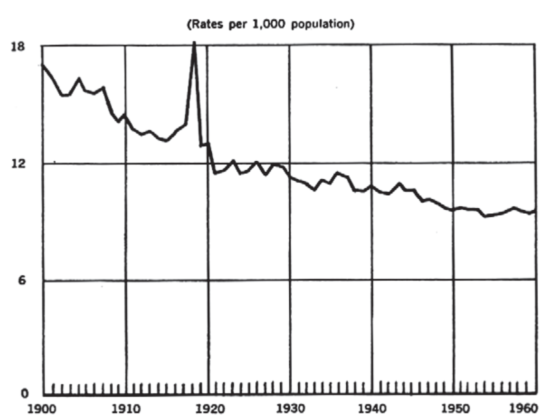

Fig. 1. Death rates: death registration states, 1900–32, and United States, 1933–60.

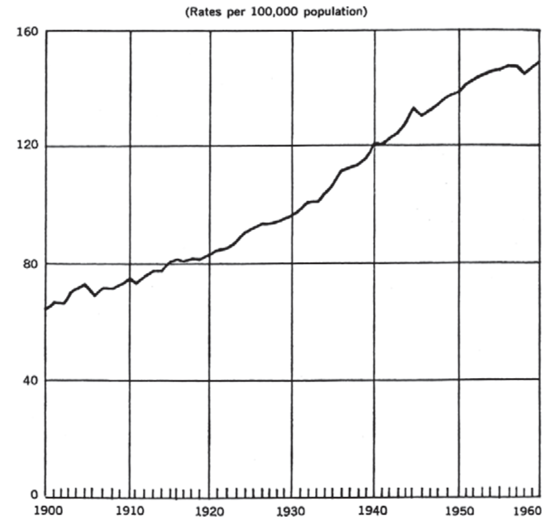

Fig. 2. Death rates for malignant neoplasms: death registration states, 1900–32, and United States, 1933–60.

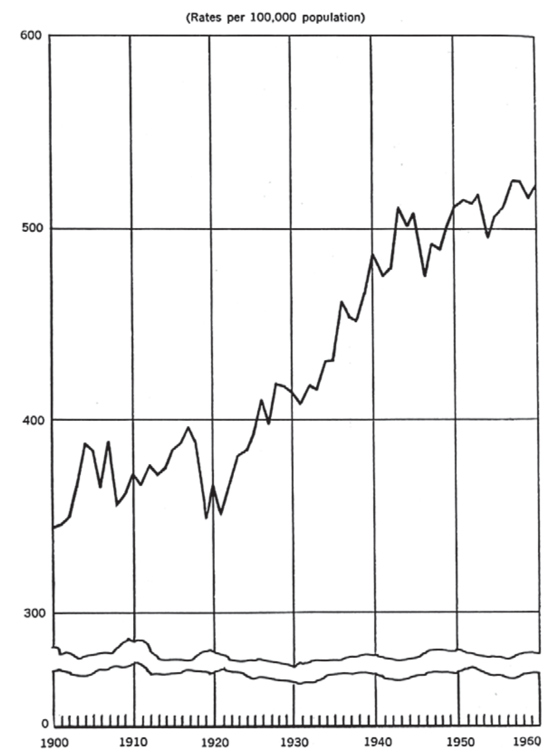

Fig. 3. Death rates for major cardiovascular renal diseases: death registration states, 1900–32, and United States, 1933–60.

electric service. In 1940 urban and rural residence information was not available for individual cancers as it was in 1930, but death rates for each cancer were available by state. They were used to calculate correlations between electric service by state and respiratory cancer, breast cancer and leukemia mortality.

All causes of death

There was no correlation between residential electrification and total death rate for urban areas, but there was a significant correlation for rural areas (r = 0.659, p = <0.0001). Fig. 5 shows the 1940 resident white death rates for urban and rural areas of states having greater than 96% of residences electrified and states having less than 50% of residences electrified. In the highly electrified states, urban and rural death rates were similar, but in low electrification states, the urban death rates were systematically higher than the rural death rates. The urban death rates were similar in both high and low electrification states.

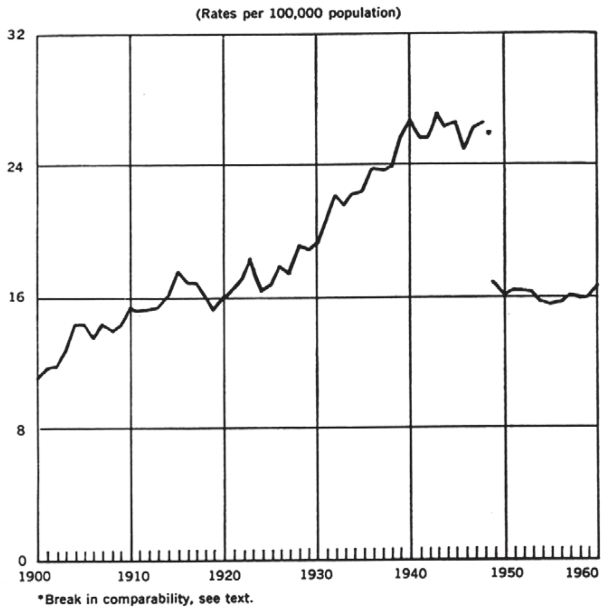

Fig. 4. Death rates for diabetes mellitus: death registration states, 1900–32, and United States, 1933–60.

All malignant neoplasms

In 1940, the urban total cancer rate was 49.2% higher than the rural rate. Both urban and rural cancer deaths rates were significantly correlated with residential electrification. Fig. 6 shows the 1940 resident white total cancer rates for urban and rural areas of states having greater than 96% of residences electrified and states having less than 50% of residences electrified. Four of the five high electrification states had similar urban and rural total cancer rates, while all the low electrification states had urban rates about twice as high as rural rates. Both urban and rural total cancer rates were lower in low electrification states than in high electrification states. Fig. 7 shows the time trend of the total cancer rate between 1920 and 1960 for Massachusetts (1940 electrification rate = 97.6%) and Louisiana (1940 electrification rate = 48.9%). The Massachusetts cancer rate was about twice that of Louisiana between 1920 and 1945. The Massachusetts rate leveled off in 1945, but the Louisiana rate increased steadily between 1920 and 1960. A declining urban–rural gradient for cancer is still evident in 1980–1990 US cancer incidence data [13]. Swedish investigators [14] have reported increasing cancer mortality and incidence time trend breaks in the latter half of the 20th century.

Table 3
1940 US white resident crude death rates per 100,000 by urban/rural residence.

Cause of death	ICD No.[a]	Urban rate	Rural rate	(%) Urban excess
All	1-200	1124.1	929.5	20.9
All cancers	47-55	145.8	97.7	49.2
Coronary disease	94	92.4	69.1	33.7
Other diseases of heart	90b,91,92a,d,e 93a,b,d,e 95a,c	217.0	162.8	33.3
Diabetes	61	33.2	20.0	66.0
Suicide	163-164	17.1	13.2	29.5
Motor vehicle accidents	170	26.6	26.3	1.1

[a] 1938 Revision International classification of disease.

Table 4
Correlation coefficients (r) 1940 crude US death rates by state by electrification for white resident deaths.

Cause	ICD No.[A]	Residence	r	r^2	p One tailed	Slope	Y intercept
All causes	1-200	Urban	0.083	0.007	0.285	0.007	11.114
		Rural	0.659	0.434	<0.0001	0.070	4.185
All cancers	45-55	Urban	0.667	0.445	<0.0001	0.883	75.970
		Rural	0.758	0.575	<0.0001	1.502	−10.040
Respiratory cancer[B]	47	State	0.611	0.374	<0.0001	0.071	1.020
Breast cancer female	50	State	0.794	0.630	<0.0001	0.170	−1.506
Diabetes	61	Urban	0.666	0.444	<0.0001	0.278	8.168
		Rural	0.693	0.480	<0.0001	0.366	−6.184
Leukemia[B]	72a	State	0.375	0.140	0.0042	0.021	1.980
Coronary artery	94	Urban	0.400	0.160	0.0024	0.494	61.570
Disease		Rural	0.781	0.610	<0.0001	1.252	25.319
Other diseases of the heart	90b, 91	Urban	0.449	0.202	0.0006	1.236	100.35
	92a,d,e 93a,b,d,e 95a,c	Rural	0.799	0.639	0.0001	2.887	−48.989
Suicide	163-4	Urban	0.077	0.006	0.2993	0.028	16.235
		Rural	0.729	0.532	<0.0001	0.181	0.299
Motor vehicle	170	Urban	−0.254	0.064	0.0408	−0.171	44.572
Accidents		Rural	0.451	0.203	0.0006	0.195	12.230

[A] International classification of diseases 1938 revision.
[B] Age adjusted death rate both sexes.

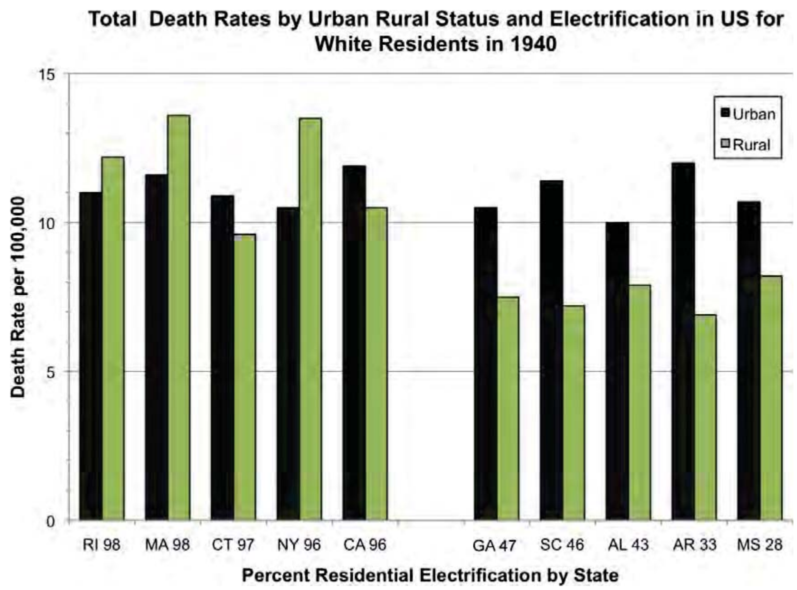

Fig. 5. All causes death rates by urban rural status and electrification in the US for white residents in 1940.

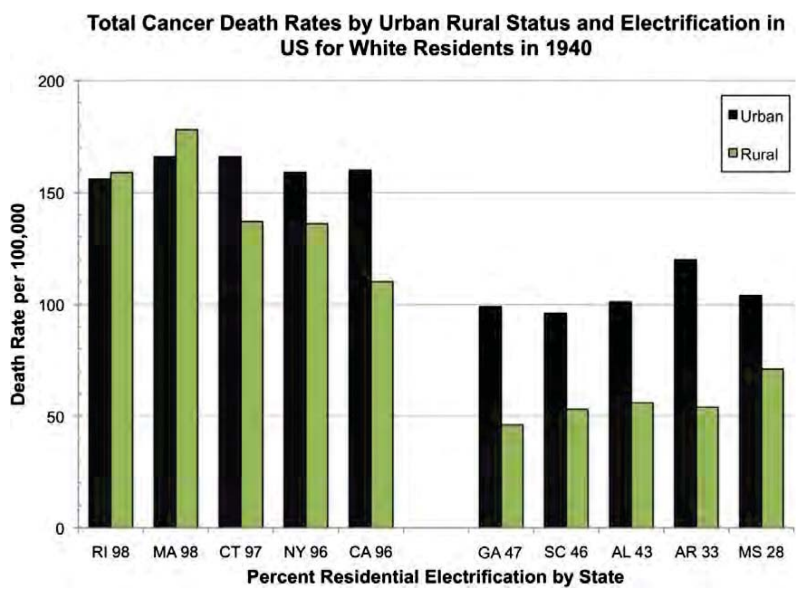

Fig. 6. Total cancer death rates by urban rural status and electrification in the US for white residents in 1940.

Respiratory cancer

No urban rural information was available for respiratory cancer, but the correlation between residential electrification and state death rates was $r = 0.611$; $p = <0.0001$. This cancer is etiologically strongly related to cigarette smoking, so the correlation with electrification is surprising. A large electrical utility worker cohort study found a high respiratory cancer incidence related to high frequency EMF transient exposure independent of cigarette smoking with a significant dose–response relationship [15].

Breast cancer

Although urban/rural information was not available for breast cancer, the 1940 state breast cancer death rates have a correlation of $r = 0.794$; $p = <0.0001$ with residential electrification. Fig. 8 shows the typical time trend of breast cancer death rates for a state with a high level of electrification (96%) and one with a low level of electrification (<50) in 1940. The California breast cancer death rate increased from 1920 to 1940, and then gradually decreased until 1960. The Tennessee breast cancer death rate is less than half of the California rate in 1920 and continues a steady increase until 1960.

Diabetes

This cause has a 66% urban excess. In spite of this, the correlation coefficients for urban and rural areas are similar at $r = 0.66$; $p = <0.0001$. There is some animal and human evidence that EMFs can effect insulin production and blood glucose levels [16]. Fig. 9

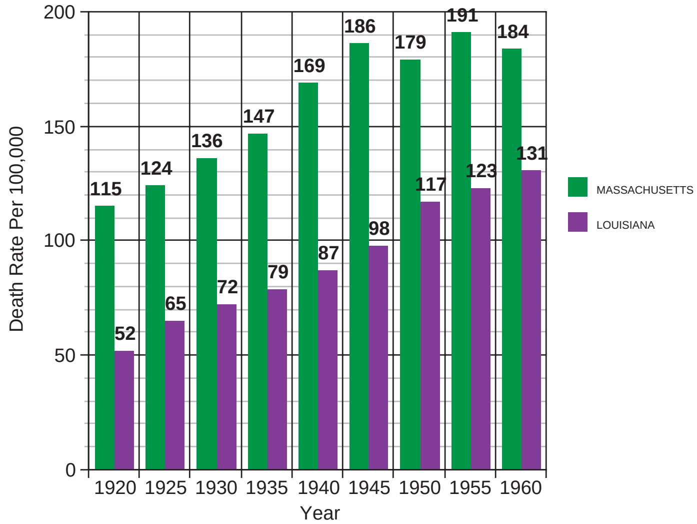

Fig. 7. US white resident total cancer death rates for Massachusetts (97.6% elect.) and Louisiana (48.9% elect.) by year.

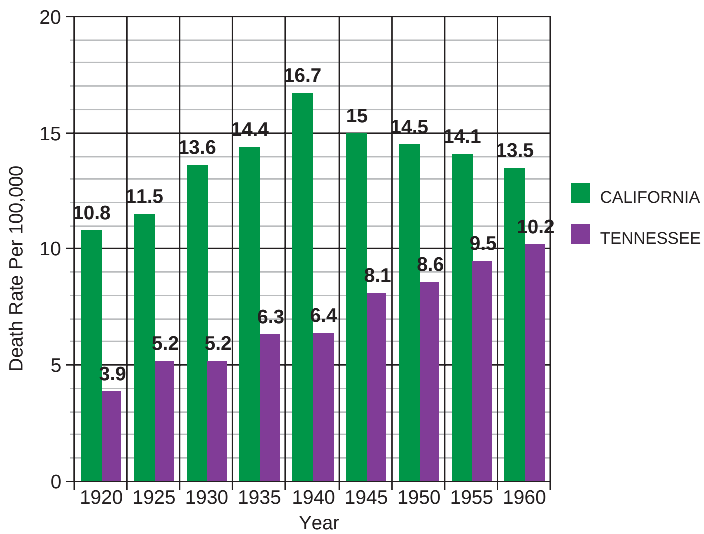

Fig. 8. US white resident breast cancer death rates for California (96% elect.) and Tennessee (50% elect.) by year.

shows that in states with low levels of electrification in 1940, the urban diabetes death rates are consistently higher than the rural rates, but are always lower than the urban and rural rates in the high electrification states.

Leukemia

Since the childhood leukemia age peak is strongly associated with residential electrification, it was interesting that the all leukemia death rate correlation was $r = 0.375$; $p = 0.0042$. Most of these deaths are in adults and are of different types of leukemia. A study of amateur radio operators showed a selective excess only of acute myelogenous leukemia [17].

Coronary artery disease and other heart disease

These two cause groups had the same percentage urban excess (33%), and very similar patterns of urban and rural correlation coefficients with residential electrification. The urban correlations were about $r = 0.4$ and rural deaths had correlations of 0.78 and 0.79, respectively. Fig. 10 shows the 1940 resident white coronary artery disease death rates for urban and rural areas of states having greater than 96% of residences electrified and states having less than 50% of residences electrified. Four of the five high electrification states had similar urban and rural total cancer rates, while all the low electrification states had urban rates about twice as high as rural rates. Urban and rural coronary artery death rates were lower in low electrification states than in high electrification states.

Suicide

The urban suicide death rate is about 30% higher than the rural rate. The urban suicide rate is not correlated with residential electrification ($r = 0.077$; $p = 0.299$), but the rural death rate is correlated with 1940 state residential electrification levels ($r = 0.729$; $p = <0.0001$). Fig. 11 shows the 1940 resident white suicide for

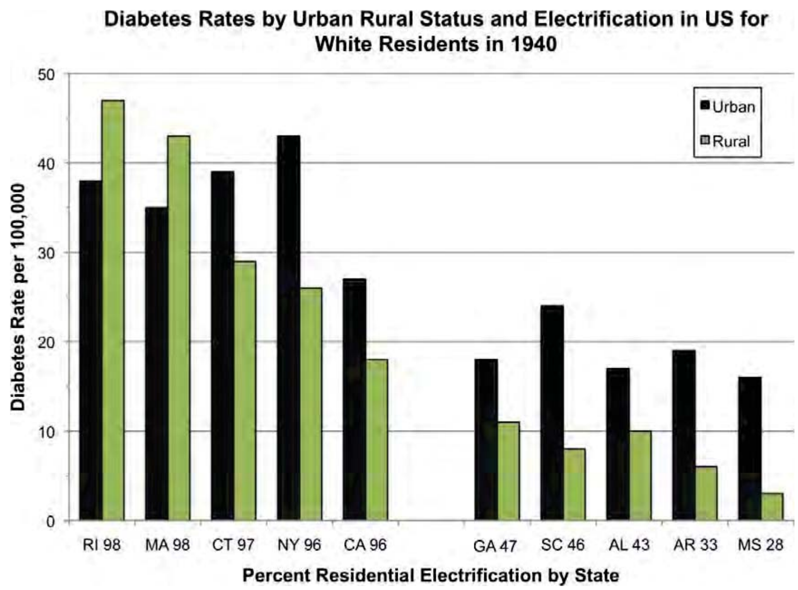

Fig. 9. Total diabetes rates by urban rural status and electrification in the US for white residents in 1940.

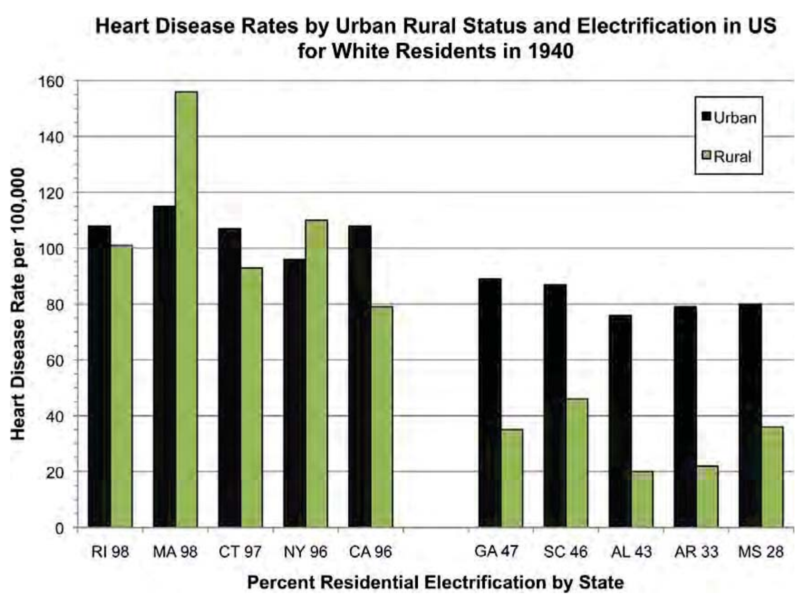

Fig. 10. Total heart disease rates by urban rural status and electrification in the US for white residents in 1940.

urban and rural areas of states having greater than 96% of residences electrified and states having less than 50% of residences electrified. In four of five high electrification states, rural suicide rates are higher than the urban rates. In all of the low electrification states, the urban rate is higher. The rural rates in the high electrification states are higher than the rural rates in the low electrification states. Fig. 12 shows X Y scatter plots for urban and rural suicide by electrification for 48 states. Suicide has been associated with both residential [18] and occupational [19] EMF exposure. Suicide is probably the visible peak of the clinical depression iceberg.

Motor vehicle accidents

Although the mortality rates are similar in urban and rural areas, the correlations with residential electrification levels are different. There is a slight negative correlation ($r = -0.254$) in urban areas and a positive correlation ($r = 0.451$) in rural areas. Since motor vehicle fatality is related to access to a vehicle and to speed. It may be that in the larger cities it was difficult to go fast enough for a fatal accident, and in rural areas especially on farms, a farmer who could afford electrification could also afford a car.

Discussion

When Edison and Tesla opened the Pandora's box of electrification in the 1880s, the US vital registration system was primitive at best, and infectious disease death rates were falling rapidly. City residents had higher mortality rates and shorter life expectancy than rural residents [8]. Rural white males in 1900 had an expectation of life at birth of over 10 years longer than urban residents.

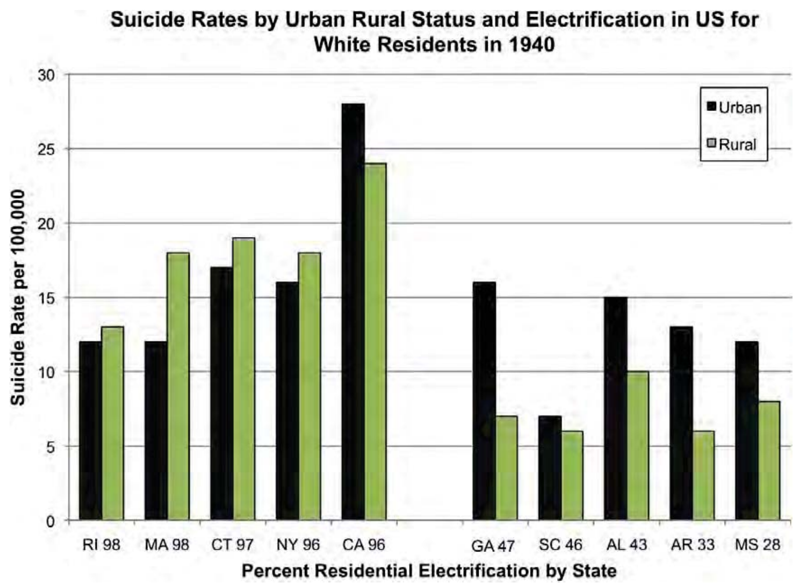

Fig. 11. Total suicide death rates by urban rural status and electrification in the US for white residents in 1940.

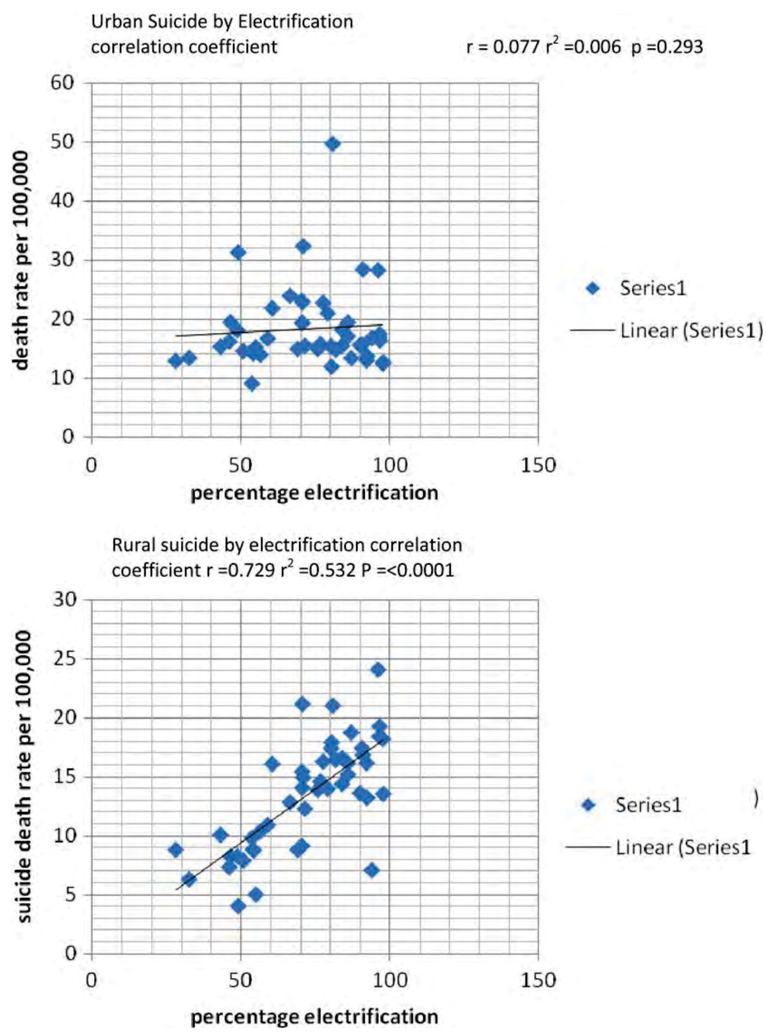

Fig. 12. 1940 US white resident urban rural suicide death rates by state and electrification.

Although the authors of the 1930 US vital statistics report noted a 58.2% cancer mortality excess in urban areas, it raised no red flags. The census bureau residential electrification data was obviously not linked to the mortality data. Epidemiologists in that era were still concerned with the communicable diseases.

Court Brown and Doll reported [20] the appearance of the childhood leukemia age peak in 1961, forty years after the US vital statistics mortality data on which it was based was available. I reported a cluster of childhood leukemia [21] a decade after it occurred, only because I looked for it. Real time or periodic analysis of national or regional vital statistics data is still only rarely done in the US.

The real surprise in this data set is that cardiovascular disease, diabetes and suicide, as well as cancer seem to be strongly related to level of residential electrification. A community-based epidemiologic study of urban rural differences in coronary heart disease and its risk factors was carried out in the mid 1980s in New Delhi, India and in a rural area 50 km away [22]. The prevalence of coronary heart disease was three times higher in the urban residents, despite the fact that the rural residents smoked more and had higher total caloric and saturated fat intakes. Most cardiovascular disease risk factors were two to three times more common in the urban residents. Rural electrification projects are still being carried out in parts of the rural area which was studied.

It seems unbelievable that mortality differences of this magnitude could go unexplained for over 70 years after they were first reported and 40 years after they were noticed. I think that in the early part of the 20th century nobody was looking for answers. By the time EMF epidemiology got started in 1979 the entire population was exposed to EMFs. Cohort studies were therefore using EMF-exposed population statistics to compute expected values, and case-control studies were comparing more exposed cases to less exposed controls. The mortality from lung cancer in two pack a day smokers is over 20 times that of non-smokers but only three times that of one pack a day smokers. After 1956, the EMF equivalent of a non-smoker ceased to exist in the US. An exception to this is the Amish who live without electricity. Like rural US residents in the 1940s, Amish males in the 1970s had very low cancer and cardiovascular disease mortality rates [23].

If this hypothesis and findings outlined here are even partially true, the explosive recent increase in radiofrequency radiation, and high frequency voltage transients sources, especially in urban areas from cell phones and towers, terrestrial antennas, wi-fi and wi-max systems, broadband internet over power lines, and personal electronic equipment, suggests that like the 20th century EMF epidemic, we may already have a 21st century epidemic of morbidity and mortality underway caused by electromagnetic fields. The good news is that many of these diseases may be preventable by environmental manipulation, if society chooses to.

Conflicts of interest statement

None declared.

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EXHIBIT 12

A New Electromagnetic Exposure Metric: High Frequency Voltage Transients Associated With Increased Cancer Incidence in Teachers in a California School

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Background *In 2003 the teachers at La Quinta, California middle school complained that they had more cancers than would be expected. A consultant for the school district denied that there was a problem.*
Objectives *To investigate the cancer incidence in the teachers, and its cause.*
Method *We conducted a retrospective study of cancer incidence in the teachers' cohort in relationship to the school's electrical environment.*
Results *Sixteen school teachers in a cohort of 137 teachers hired in 1988 through 2005 were diagnosed with 18 cancers. The observed to expected (O/E) risk ratio for all cancers was 2.78 ($P = 0.000098$), while the O/E risk ratio for malignant melanoma was 9.8 ($P = 0.0008$). Thyroid cancer had a risk ratio of 13.3 ($P = 0.0098$), and uterine cancer had a risk ratio of 9.2 ($P = 0.019$). Sixty Hertz magnetic fields showed no association with cancer incidence. A new exposure metric, high frequency voltage transients, did show a positive correlation to cancer incidence. A cohort cancer incidence analysis of the teacher population showed a positive trend ($P = 7.1 \times 10^{-10}$) of increasing cancer risk with increasing cumulative exposure to high frequency voltage transients on the classroom's electrical wiring measured with a Graham/Stetzer (G/S) meter. The attributable risk of cancer associated with this exposure was 64%. A single year of employment at this school increased a teacher's cancer risk by 21%.*
Conclusion *The cancer incidence in the teachers at this school is unusually high and is strongly associated with high frequency voltage transients, which may be a universal carcinogen, similar to ionizing radiation.* Am. J. Ind. Med. 2008. *© 2008 Wiley-Liss, Inc.*

KEY WORDS: high frequency voltage transients; electricity; dirty power; cancer; school teachers; carcinogen

Abbreviations: EMF, electromagnetic fields; O, observed cases; E, expected cases; O/E, risk ratio; p, probability; Hz, Hertz or cycles per second; OSHA, Occupational Safety and Health Administration; OCMAP, occupational mortality analysis program; AM, amplitude modulation; GS units, Graham/Stetzer units; G/S meter, Graham/Stetzer meter; MS II, Micro-surge II meter; mG, milligauss; EKG, electrocardiogram; LQMS, La Quinta Middle School.

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BACKGROUND

Since the 1979 Wertheimer–Leeper study [Wertheimer and Leeper, 1979] there has been concern that exposure to power frequency (50/60 Hz) EMFs, especially magnetic fields, may contribute to adverse health effects including cancer. Until now, the most commonly used exposure metric has been the time-weighted average of the power-frequency magnetic field. However, the low risk ratios in most studies suggest that magnetic fields might be a surrogate for a more important metric. In this paper we present evidence that a new exposure metric, high frequency voltage transients existing on electrical power wiring, is an important predictor of cancer incidence in an exposed population.

The new metric, GS units, used in this investigation is measured with a Graham/Stetzer meter (G/S meter) also known as a Microsurge II meter (MS II meter), which is plugged into electric outlets [Graham, 2005]. This meter displays the average rate of change of these high frequency voltage transients that exist everywhere on electric power wiring. High frequency voltage transients found on electrical wiring both inside and outside of buildings are caused by an interruption of electrical current flow. The electrical utility industry has referred to these transients as ''dirty power.''

There are many sources of ''dirty power'' in today's electrical equipment. Examples of electrical equipment designed to operate with interrupted current flow are light dimmer switches that interrupt the current twice per cycle (120 times/s), power saving compact fluorescent lights that interrupt the current at least 20,000 times/s, halogen lamps, electronic transformers and most electronic equipment manufactured since the mid-1980s that use switching power supplies. Dirty power generated by electrical equipment in a building is distributed throughout the building on the electric wiring. Dirty power generated outside the building enters the building on electric wiring and through ground rods and conductive plumbing, while within buildings, it is usually the result of interrupted current generated by electrical appliances and equipment.

Each interruption of current flow results in a voltage spike described by the equation $V = L \times di/dt$, where V is the voltage, L is the inductance of the electrical wiring circuit and di/dt is the rate of change of the interrupted current. The voltage spike decays in an oscillatory manner. The oscillation frequency is the resonant frequency of the electrical circuit. The G/S meter measures the average magnitude of the rate of change of voltage as a function of time (dV/dT). This preferentially measures the higher frequency transients. The measurements of dV/dT read by the meter are defined as GS (Graham/Stetzer) units.

The bandwidth of the G/S meter is in the frequency range of these decaying oscillations. Figure 1 shows a two-channel oscilloscope display. One channel displays the 60 Hz voltage on an electrical outlet while the other channel with a 10 kHz hi-pass filter between the oscilloscope and the electrical outlet, displays the high frequency voltage transients on the same electrical outlet [Havas and Stetzer, 2004, reproduced with permission].

Although no other published studies have measured high frequency voltage transients and risk of cancer, one study of electric utility workers exposed to transients from pulsed

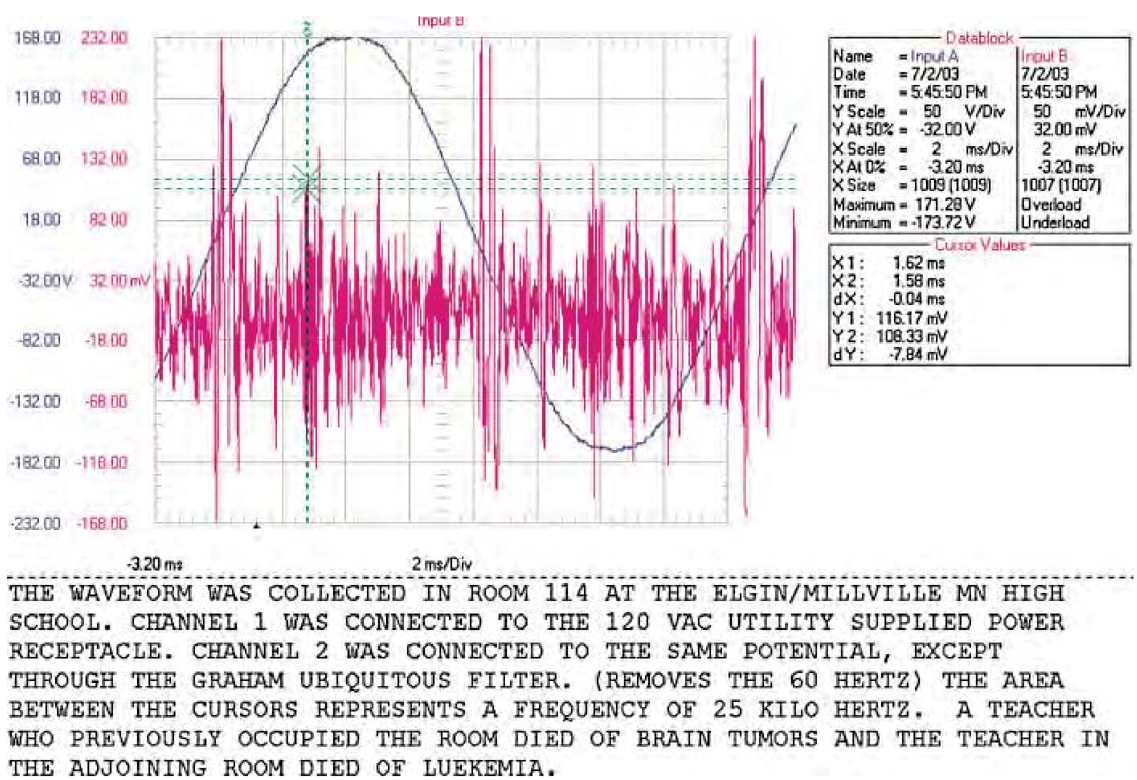


FIGURE 1. Oscilloscope display of dirty power: 60 Hz electrical power (channel 1) with concurrent high frequency voltage transients (channel 2). A 10 kHz hi-pass filter was used on channel 2 in order to filter out the 60 Hz voltage and its harmonics. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

electromagnetic fields found an increased incidence of lung cancer among exposed workers [Armstrong et al., 1994].

INTRODUCTION

In February 2004, a Palm Springs, California newspaper, The Desert Sun, printed an article titled, ‘‘Specialist discounts cancer cluster at school,’’ in which a local tumor registry epidemiologist claimed that there was no cancer cluster or increased cancer incidence at the school [Perrault, 2004]. An Internet search revealed that the teacher population at La Quinta Middle School (LQMS) was too small to generate the 11 teachers with cancer who were reported in the article. The school was opened in 1988 with 20 teachers hired that year. For the first 2 years, the school operated in three temporary buildings, one of which remains. In 1990, a newly constructed school opened. In 2003, the teachers complained to school district management that they believed that they had too many cancers. Repeated requests to the school administration for physical access to the school and for teachers' information were denied. We contacted the teachers, and with their help, the cancers in the group were characterized. One teacher suggested using yearbooks to develop population-at-risk counts for calculating expected cancers. We were anxious to assess the electrical environment at the school, since elevated power frequency magnetic field exposure with a positive correlation between duration of exposure and cancer incidence had been reported in first floor office workers who worked in strong magnetic fields above three basement-mounted 12,000 V transformers [Milham, 1996]. We also wanted to use a new electrical measurement tool, the Graham/Stetzer meter, which measures high frequency voltage transients.

The Graham/Stetzer Microsurge II meter measures the average rate of change of the transients in Graham/Stetzer units (GS units). Anecdotal reports had linked dirty power exposure with a number of illnesses [Havas and Stetzer, 2004]. We decided to investigate whether power frequency magnetic field exposure or dirty power exposure could explain the cancer increase in the school teachers.

METHODS

After the school administration (Desert Sands Unified School District) had refused a number of requests to assist in helping us evaluate the cancers reported by the teachers, we were invited by a teacher to visit the school after hours to make magnetic field and dirty power measurements. During that visit, we noted that, with the exception of one classroom near the electrical service room, the classroom magnetic field levels were uniformly low, but the dirty power levels were very high, giving many overload readings. When we reported this to Dr. Doris Wilson, then the superintendent of schools (retired December, 2007), one of us (SM) was threatened with prosecution for ‘‘unlawful.. trespass,’’ and the teacher who had invited us into the school received a letter of reprimand. The teachers then filed a California OSHA complaint which ultimately lead to a thorough measurement of magnetic fields and dirty power levels at the school by the California Department of Health Services which provided the exposure data for this study. They also provided comparison dirty power data from residences and an office building, and expedited tumor registry confirmation of cancer cases.

Classrooms were measured at different times using 3 meters: an FW Bell model 4080 tri-axial Gaussmeter, a Dexsil 310 Gaussmeter, and a Graham-Stetzer (G/S) meter. The Bell meter measures magnetic fields between 25 and 1,000 Hz. The Dexsil meter measures magnetic fields between 30 and 300 Hz. The G/S meter measures the average rate of change of the high frequency voltage transients between 4 and 150 KHz.

All measurements of high frequency voltage transients were made with the G/S meter. This meter was plugged into outlets, and a liquid crystal display was read. All measurements reported were in GS units. The average value was reported where more than one measurement was made in a classroom.

We measured seven classrooms in February 2005 using the Bell meter and the G/S meter. Later in 2005, the teachers measured 37 rooms using the same meters. On June 8, 2006, electrical consultants for the school district and the California Department of Health Services (Dr. Raymond Neutra) repeated the survey using the G/S meter and a Dexsil 320 Gaussmeter, measuring 51 rooms. We used results of this June 8, 2006 sampling in our exposure calculations, since all classrooms were sampled, multiple outlets per room were sampled, and an experienced team did the sampling. Additionally, GS readings were taken at Griffin Elementary school near Olympia, Washington, and Dr. Raymond Neutra provided GS readings for his Richmond California office building and 125 private California residences measured in another Northern California study.

All the cancer case information was developed by personal, telephone, and E-mail contact with the teachers or their families without any assistance from the school district. The local tumor registry verified all the cancer cases with the exception of one case diagnosed out of state and the two cases reported in 2007. The out-of state case was verified by pathologic information provided by the treating hospital. The teachers gathered population-at-risk information (age at hire, year of hire, vital status, date of diagnosis, date of death, and termination year) from yearbooks and from personal contact. The teachers also provided a history of classroom assignments for all teachers from annual classroom assignment rosters (academic years 1990–1991 to 2006–2007) generated by the school administration. The school administration provided a listing of school employees, including the teachers, to the regional tumor registry after the teachers involved the state health agency by submitting an OSHA complaint. The information we obtained anecdotally from the teachers, yearbooks, and classroom assignment rosters was nearly identical to that given to the tumor registry. None of the cancer cases were ascertained initially through the cancer registry search.

Published cancer incidence rates by age, sex, and race for all cancers, as well as for malignant melanoma, thyroid, uterine, breast, colon, ovarian cancers, and non-Hodgkin's lymphoma (NHL) were obtained from a California Cancer Registry publication [Kwong et al., 2001]. We estimated the expected cancer rate for each teacher by applying year, age, sex, and race-specific cancer incidence rates from hire date until June 2007, or until death. We then summed each teacher's expected cancer rate for the total cohort.

Using the California cancer incidence data, the school teacher data, and the GS exposure data, we calculated cancer incidence and risks. A replicate data set was sent to Dr. Gary Marsh and to Mike Cunningham at the University of Pittsburgh School of Public Health for independent analysis using OCMAP software. We calculated cancer risk ratios by duration of employment and by cumulative GS unit-years of exposure. We calculated an attributable risk percent using the frequencies of total observed and expected cancers, and performed trend tests [Breslow and Day, 1987] for cancer risk versus duration of employment and cumulative GS unit-years of exposure. Poisson *P* values were calculated using the Stat Trek website (Stat Trek, 2007). We also performed a linear regression of cancer risk by duration of employment in years and by time-weighted exposure in GS unit-years.

Since neither author had a current institutional affiliation, institutional review board approval was not possible. The teachers requested the study, and their participation in the study was both voluntary and complete. All the active teachers at the school signed the Cal OSHA request. The authors fully explained the nature of the study to study participants and offered no remuneration to the teachers for participation in the study. The authors maintained strict confidentiality of all medical and personal information provided to us by the teachers, and removed personal identifiers from the data set which was analyzed by the University of Pittsburgh. Possession of personal medical information was limited to the two authors. No patient-specific information was obtained from the tumor registry. With the individual's permission we provided the registry with case information for a teacher with malignant melanoma diagnosed out of state. The exposure information was provided by the California Department of Health Services. The basic findings of the study were presented to the Desert Sands Unified School District School Board and at a public meeting arranged by the teachers.

RESULTS

Electrical Measurements

In our seven-room survey of the school in 2005, magnetic field readings were as high as 177 mG in a classroom adjacent to the electrical service room. A number of outlets had overload readings with the G/S meter. Magnetic fields were not elevated (>3.0 mG) in the interior space of any of the classrooms except in the classroom adjacent to the electrical service room, and near classroom electrical appliances such as overhead transparency projectors. There was no association between the risk of cancer and 60 Hz magnetic field exposures in this cohort, since the classroom magnetic field exposures were the same for teachers with and without cancer (results not shown).

This school had very high GS readings and an association between high frequency voltage transient exposure in the teachers and risk of cancer. The G/S meter gives readings in the range from 0 to 1,999 GS units. The case school had 13 of 51 measured rooms with at least one electrical outlet measuring "overload" (≥2,000 GS units). These readings were high compared to another school near Olympia Washington, a Richmond California office building, and private residences in Northern California (Table I). Altogether, 631 rooms were surveyed for this study. Only 17 (2.69%) of the 631 rooms had an "overload" (maximum, ≥2,000 GS units) reading. Applying this percentage to the 51 rooms surveyed at the case school, we would expect 1.4 rooms at the school to have overload GS readings ($0.0269 \times 51 = 1.37$). However, thirteen rooms (25%) measured at the case school had "overload" measurements above the highest value (1,999 GS units) that the G/S meter can

TABLE I. Graham/Stetzer Meter Readings: Median Values in Schools, Homes and an Office Building

Place	Homes	Office bldg	Olympia WA School	LQMS	Total
No. of rooms surveyed	500	39	41	51	531
Median GS units	159	210	160	750	<270[a]
Rooms with overload GS units (≥2,000)	4	0	0	13*	17

[a]Excludes homes as specific room data was not available.
*$P = 3.14 \times 10^{-9}$.

TABLE II. Risk of Cancer by Type Among Teachers at La Quinta Middle School

Cancer	Observed	Expected	Risk ratio (O/E)	*P*-value
All cancers	18	6.51	2.78*	0.000098
Malignant melanoma	4	0.41	9.76*	0.0008
Thyroid cancer	2	0.15	13.3*	0.011
Uterus cancer	2	0.22	9.19*	0.019
Female breast cancer	2	1.5	1.34	0.24
All cancers less melanoma	14	6.10	2.30*	0.0025

*$P \leq 0.05$.

measure. This is a highly statistically significant excess over expectation (Poisson $P = 3.14 \times 10^{-9}$).

We noticed AM radio interference in the vicinity of the school. A teacher also reported similar radio interference in his classroom and in the field near his ground floor classroom. In May 2007, he reported that 11 of 15 outlets in his classroom overloaded the G/S meter. An AM radio tuned off station is a sensitive detector of dirty power, giving a loud buzzing noise in the presence of dirty power sources even though the AM band is beyond the bandwidth of the G/S meter.

Cancer Incidence

Three more teachers were diagnosed with cancer in 2005 after the first 11 cancer diagnoses were reported, and another former teacher (diagnosed out-of-state in 2000) was reported by a family member employed in the school system. One cancer was diagnosed in 2006 and two more in 2007. In the years 1988–2005, 137 teachers were employed at the school. The 18 cancers in the 16 teachers were: 4 malignant melanomas, 2 female breast cancers, 2 cancers of the thyroid, 2 uterine cancers and one each of Burkitt's lymphoma (a type of non-Hodgkins lymphoma), polycythemia vera, multiple myeloma, leiomyosarcoma and cancer of the colon, pancreas, ovary and larynx. Two teachers had two primary cancers each: malignant melanoma and multiple myeloma, and colon and pancreatic cancer. Four teachers had died of cancer through August 2007. There have been no non-cancer deaths to date.

The teachers' cohort accumulated 1,576 teacher-years of risk between September 1988 and June 2007 based on a 12-month academic year. Average age at hire was 36 years. In 2007, the average age of the cohort was 47.5 years.

When we applied total cancer and specific cancer incidence rates by year, age, sex, race, and adjusted for cohort ageing, we found an estimate of 6.5 expected cancers, 0.41 melanomas, 0.15 thyroid cancers, 0.22 uterine cancers, and 1.5 female breast cancers (Table II). For all cancers, the risk ratio (Observed/Expected = 18/6.5) was 2.78 ($P =$ 0.000098, Poisson test); for melanoma, (O/E = 4/0.41) was 9.8 ($P = 0.0008$, Poisson test); for thyroid cancer (O/E = 2/0.15) was 13.3 ($P = 0.0011$, Poisson test); for uterine cancer (O/E = 2/0.22), was 9.19 ($P = 0.019$, Poisson test).

Table III shows the cancer risk among the teachers by duration of employment. Half the teachers worked at the school for less than 3 years (average 1.52 years). The cancer risk increases with duration of employment, as is expected when there is exposure to an occupational carcinogen. The cancer risk ratio rose from 1.7 for less than 3 years, to 2.9 for 3–14 years, to 4.2 for 15+ years of employment. There was a positive trend of increasing cancer incidence with increasing duration of employment ($P = 4.6 \times 10^{-10}$). A single year of employment at this school increases a teacher's risk of cancer by 21%.

Using the June 8, 2006 survey data (Table IV), the cancer risk of a teacher having ever worked in a room with at least one outlet with an overload GS reading (≥2000 GS units) and employed for 10 years or more, was 7.1 ($P = 0.00007$, Poisson test). In this group, there were six teachers diagnosed

TABLE III. Cancer Risk by Duration of Employment

Time at school	Average time	Teachers	% of teachers	Cancer observed	Cancer expected	Risk ratio (O/E)	Poisson p
<3 years	1.52 years	68	49.6	4	2.34	1.72	0.12
3–14 years	7.48 years	56	40.9	9	3.14	2.87*	0.0037
15+ years	16.77 years	12	8.8	5	1.02	4.89*	0.0034
Total		137	100	18	6.51	2.78*	0.000098

Positive trend test (Chi square with one degree of freedom = 38.8, $P = 4.61 \times 10^{-10}$).
*$P \leq 0.05$.

TABLE IV. Cancer in Teachers Who Ever Taught in Classrooms With at Least One Overload GS Reading ($\geq$2000 GS Units) by Duration of Employment

Ever in a room >2,000 GS units	Employed 10 + years	Total teachers	Cancers observed	Cancers expected	Risk ratio (O/E)	Poisson p
Yes	Yes	10	7[a]	0.988	7.1*	0.00007
Yes	No	30	3[a]	0.939	3.2	0.054
Total		40	10	1.93	5.1*	0.00003
No	Yes	19	2	1.28	1.6	0.23
No	No	78	6	3.25	1.8	0.063
Total		97	8	4.56	1.8*	0.047
Grand total		137	18	6.49	2.8*	0.000098

[a]One teacher had two primary cancers.
*$P < 0.05$.

with a total of seven cancers, and four teachers without a cancer diagnosis, who were employed for 10 or more years and who ever worked in one of these rooms. Five teachers had one primary cancer and one teacher had two primary cancers. These teachers made up 7.3% of the teachers' population (10/137) but had 7 cancers or 39% (7/18) of the total cancers. The 10 teachers who worked in an overload classroom for 10 years or more had 7 cancers when 0.99 would have been expected ($P = 6.8 \times 10^{-5}$ Poisson test). The risk ratio for the 8 teachers with cancer and 32 teachers without cancer, who ever worked in a room with an overload GS reading, regardless of the time at the school, was 5.1 ($P = 0.00003$, Poisson test). The risk ratio for 8 teachers with cancer and 89 teachers without cancer who never worked in a room with an overload G-S reading was 1.8 ($P = 0.047$, Poisson test). Teachers who never worked in an overload classroom also had a statistically significantly increased risk of cancer.

A positive dose-response was seen between the risk of cancer and the cumulative GS exposure (Table V). Three categories of cumulative GS unit-years of exposure were selected: <5,000, 5,000 to 10,000, and more than 10,000 cumulative GS unit-years. We found elevated risk ratios of 2.0, 5.0, and 4.2, respectively, all statistically significant, for each category. There was a positive trend of increasing cancer incidence with increasing cumulative GS unit-years of exposure ($P = 7.1 \times 10^{-10}$). An exposure of 1,000 GS unit-years increased a teacher's cancer risk by 13%. Working in a room with a GS overload ($\geq$2,000 GS units) for 1 year increased cancer risk by 26%.

An attributable risk percentage was calculated: (observed cancers-expected cancers)/observed cancers = (18−6.51)/18 = 63.8%.

The fact that these cancer incidence findings were generated by a single day of G/S meter readings made on June 8, 2006 suggests that the readings were fairly constant over time since the school was built in 1990. For example, if the 13 classrooms which overloaded the meter on June 8, 2006 were not the same since the start of the study and constant throughout, the cancer risk of teachers who ever worked in the overload rooms would have been the same as the teachers who never worked in an overload room.

Although teachers with melanoma and cancers of the thyroid, and uterus, had very high, statistically significant risk ratios, there was nothing exceptional about their age at hire, duration of employment, or cumulative GS exposure. However, thyroid cancer and melanoma had relatively short latency times compared to the average latency time for all 18 cancers. The average latency time between start of

TABLE V. Observed and Expected Cancers by Cumulative GS Exposure (GS Unit-Years)

Exposure group	<5,000 GS unit-years	5,000 to 10,000	>10,000 GS unit-years	Total
Average GS unit-years	914	7,007	15,483	
Cancers obs.	9	4	5	18
Cancers exp.	4.507	0.799	1.20	6.49
Risk ratio (O/E)	2.01*	5.00*	4.17*	2.78*
Poisson p	0.0229	0.0076	0.0062	0.000098

Positive trend test (Chi square with one degree of freedom = 38.0, $P = 7.1 \times 10^{-10}$).
*$P < 0.05$.

employment at the school and diagnosis for all cancers was 9.7 years. The average latency time for thyroid cancer was 3.0 years and for melanoma it was 7.3 years (with three of the four cases diagnosed at 2, 5, and 5 years).

An independent analysis of this data set by the University of Pittsburgh School of Public Health using OCMAP software supported our findings.

DISCUSSION

Because of access denial, we have no information about the source, or characterization of the high frequency voltage transients. We can assume, because the school uses metal conduit to contain the electrical wiring, that any resultant radiated electric fields from these high frequency voltage transients would radiate mainly from the power cords and from electrical equipment using the power cords within a classroom.

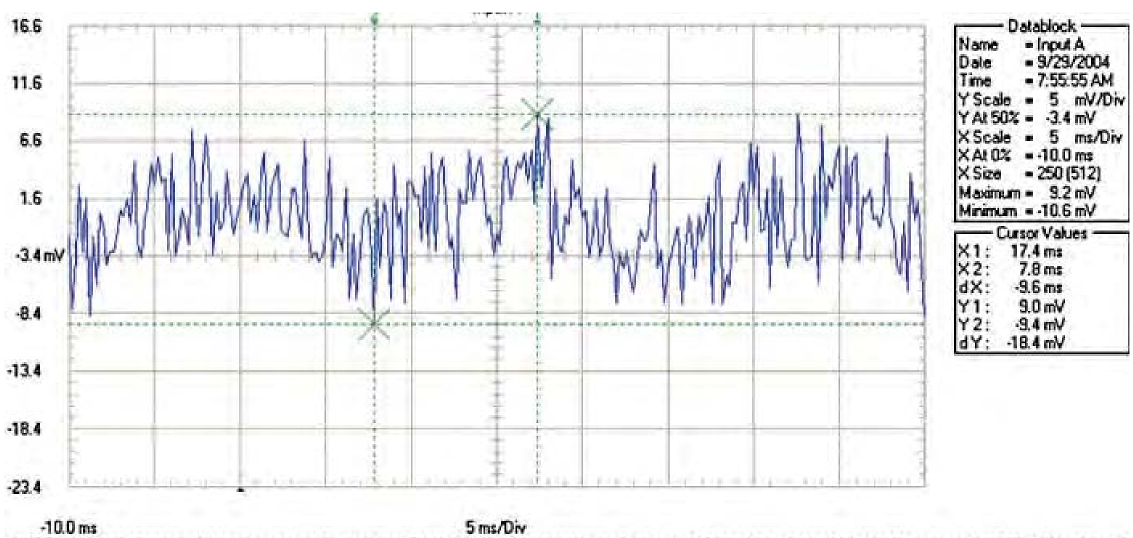
The school's GS readings of high frequency voltage transients are much higher than in other tested places (Table I). Also, teachers in the case school who were employed for over 10 years and who had ever worked in a room with an overload GS reading had a much higher rate of cancer. They made up 7.3% of the cohort but experienced 39% of all cancers.

The relatively short latency time of melanoma and thyroid cancers suggests that these cancers may be more sensitive to the effects of high frequency voltage transients than the other cancers seen in this population.

In occupational cohort studies, it is very unusual to have a number of different cancers with an increased risk. An exception to this is that cohorts exposed to ionizing radiation show an increased incidence of a number of different cancers. The three cancers in this cohort with significantly elevated incidence, malignant melanoma, thyroid cancer and uterine cancer, also have significantly elevated incidence in the large California school employees cohort [Reynolds et al., 1999].

These cancer risk estimates are probably low because 23 of the 137 members of the cohort remain untraced. Since exposure was calculated based on 7 days a week for a year, this will overstate the actual teachers' exposure of 5 days a week for 9 months a year.

We could not study field exposures in the classrooms since we were denied access to the school. We postulate that the dirty power in the classroom wiring exerted its effect by capacitive coupling which induced electrical currents in the



The waveform was recorded between 2 EKG patches placed on the ankles of XXXXXX XXXXXXXXX standing in front of his kitchen sink at his home near Bright Ontario. It shows a distorted 60 cycle sine wave containing high frequencies applied to each foot, allowing high frequency current to freely oscillate up one leg and down the other. XXXXXX has been diagnosed with prostrate cancer since moving to the house in less than a year. He was standing with feet shoulder width apart, wearing shoes, at the time of the readings. The amplitude increased as the feet were placed farther apart.

FIGURE 2. Oscilliscope display of 60 Hz current distorted with high frequencies taken between EKG patches applied to the ankles of a man standing with shoes on at a kitchen sink. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

teachers' bodies. The energy that is capacitively coupled to the teachers' bodies is proportional to the frequency. It is this characteristic that highlights the usefulness of the G/S meter. High frequency dirty power travels along the electrical distribution system in and between buildings and through the ground. Humans and conducting objects in contact with the ground become part of the circuit. Figure 2 [Havas and Stetzer, 2004, reproduced with permission] shows an oscilloscope tracing taken between EKG patches on the ankles of a man wearing shoes, standing at a kitchen sink. The 60 Hz sine wave is distorted by high frequencies, which allows high frequency currents to oscillate up one leg and down the other between the EKG patches.

Although not demonstrated in this data set, dirty power levels are usually higher in environments with high levels of 60 Hz magnetic fields. Many of the electronic devices which generate magnetic fields also inject dirty power into the utility wiring. Magnetic fields may, therefore, be a surrogate for dirty power exposures. In future studies of the EMF-cancer association, dirty power levels should be studied along with magnetic fields.

The question of cancer incidence in students who attended La Quinta Middle School for 3 years has not been addressed.

CONCLUSION

The cancer incidence in the teachers at this school is unusually high and is strongly associated with exposure to high frequency voltage transients. In the 28 years since electromagnetic fields (EMFs) were first associated with cancer, a number of exposure metrics have been suggested. If our findings are substantiated, high frequency voltage transients are a new and important exposure metric and a possible universal human carcinogen similar to ionizing radiation.

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EXHIBIT 13

Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States

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Large areas of public land are currently being permitted or evaluated for utility-scale solar energy development (USSED) in the southwestern United States, including areas with high biodiversity and protected species. However, peer-reviewed studies of the effects of USSED on wildlife are lacking. The potential effects of the construction and the eventual decommissioning of solar energy facilities include the direct mortality of wildlife; environmental impacts of fugitive dust and dust suppressants; destruction and modification of habitat, including the impacts of roads; and off-site impacts related to construction material acquisition, processing, and transportation. The potential effects of the operation and maintenance of the facilities include habitat fragmentation and barriers to gene flow, increased noise, electromagnetic field generation, microclimate alteration, pollution, water consumption, and fire. Facility design effects, the efficacy of site-selection criteria, and the cumulative effects of USSED on regional wildlife populations are unknown. Currently available peer-reviewed data are insufficient to allow a rigorous assessment of the impact of USSED on wildlife.

Keywords: solar energy development, Mojave Desert, Sonoran Desert, wildlife, desert tortoises

The United States is poised to develop new renewable energy facilities at an unprecedented rate, including in potentially large areas of public land in the Southwest. This quantum leap is driven by escalating costs and demand for traditional energy sources from fossil fuels and by concerns over global climate change. Attention is focused largely on renewable forms of energy, especially solar energy. The potential for utility-scale solar energy development (USSED) and operation (USSEDO) is particularly high in the southwestern United States, where solar energy potential is high (USDOI and USDOE 2011a) and is already being harnessed in some areas. However, the potential for USSEDO conflicts with natural resources, especially wildlife, is also high, given the exceptional biodiversity (Mittermeier et al. 2002) and sensitivity (Lovich and Bainbridge 1999) of arid Southwest ecosystems, especially the Mojave (Randall et al. 2010) and Sonoran Deserts, which are already stressed by climate and human changes (CBI 2010). In addition, the desert Southwest is identified as a "hotspot" for threatened and endangered species in the United States (Flather et al. 1998). For these reasons, planning efforts should consider ways to minimize USSEDO impacts on wildlife (CBI 2010). Paradoxically, the implementation of large-scale solar energy development as an "environmentally friendly" alternative to conventional energy sources may actually increase environmental degradation on a local and on a regional scale (Bezdek 1993, Abbasi and Abbasi 2000) with concomitant negative effects on wildlife.

A logical first step in evaluating the effects of USSEDO on wildlife is to assess the existing scientific knowledge. As renewable energy development proceeds rapidly worldwide, information is slowly accumulating on the effects of USSEDO on the environment (for reviews, see Harte and Jassby 1978, Pimentel et al. 1994, Abbasi and Abbasi 2000). Gill (2005) noted that although the number of peer-reviewed publications on renewable energy has increased dramatically since 1991, only 7.6% of all publications on the topic covered environmental impacts, only 4.0% included discussions of ecological implications, and less than 1.0% contained information on environmental risks. A great deal of information on USSEDO exists in environmental compliance documents and other unpublished, non-peer-reviewed "gray" literature sources. Published scientific information on the effects on wildlife of any form of renewable energy development, including that of wind energy, is scant (Kuvlesky et al. 2007). The vast majority of the published research on wildlife and renewable energy development has been focused on the effects of wind energy development on birds (Drewitt and Langston 2006) and bats (Kunz et al. 2007) because of their sensitivity to aerial impacts. In contrast, almost no information is available on the effects of solar energy development on wildlife.

From a conservation standpoint, one of the most important species in the desert Southwest is Agassiz's desert

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tortoise (*Gopherus agassizii*; figure 1). Distributed north and west of the Colorado River, the species was listed as *threatened* under the US Endangered Species Act in 1990. Because of its protected status, Agassiz's desert tortoise acts as an "umbrella species," extending protection to other plants and animals within its range (Tracy and Brussard, 1994). The newly described Morafka's desert tortoise (*Gopherus morafkai*; Murphy et al. 2011) is another species of significant conservation concern in the desert Southwest, found east of the Colorado River. Both tortoises are important as ecological engineers who construct burrows that provide shelter to many other animal species, which allows them to escape the temperature extremes of the desert (Ernst and Lovich 2009). The importance of these tortoises is thus greatly disproportionate to their intrinsic value as species. By virtue of their protected status, Agassiz's desert tortoises have a significant impact on regulatory issues in the listed portion of their range, yet little is known about the effects of USSEDO on the species, even a quarter century after the recognition of that deficiency (Pearson 1986). Large areas of habitat occupied by Agassiz's desert tortoise in particular have potential for development of USSED (figure 2).

*Figure 1. Agassiz's desert tortoise (*Gopherus agassizii*). Large areas of desert tortoise habitat are developed or being evaluated for renewable energy development, including for wind and solar energy. Photograph: Jeffrey E. Lovich.*

In this article, we review the state of knowledge about the known and potential effects, both direct and indirect, of USSEDO on wildlife (table 1). Our review is based on information published primarily in peer-reviewed scientific journals for both energy and wildlife professionals. Agassiz's desert tortoise is periodically highlighted in our review because of its protected status, wide distribution in areas considered for USSEDO in the desert Southwest, and well-studied status (Ernst and Lovich 2009). In addition, we identify gaps in our understanding of the effects of USSEDO on wildlife and suggest questions that will guide future research toward a goal of mitigating or minimizing the negative effects on wildlife.

Background on proposed energy-development potential in the southwestern United States

The blueprint for evaluating and permitting the development of solar energy on public land in the region, as is required under the US National Environmental Policy Act (USEPA 2010), began in a draft environmental impact statement (EIS) prepared by two federal agencies (USDOI and USDOE 2011a). The purpose of the EIS is to "develop a new Solar Energy Program to further support utility-scale solar energy development on BLM [US Bureau of Land

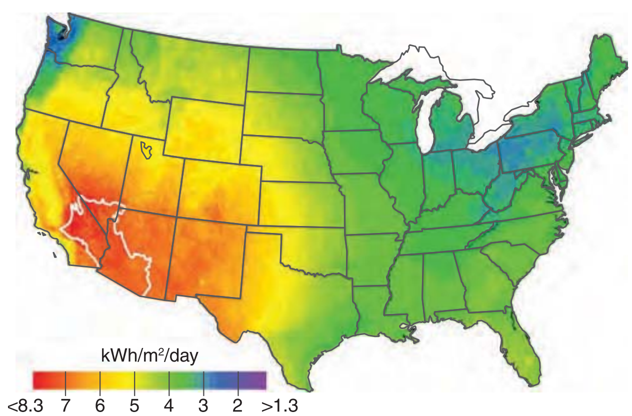

Figure 2. Concentrating solar energy potential (in kilowatt-hours per square meter per day [kWh/m²/day]) of the United States. The map shows the annual average direct normal solar resource data based on a 10-kilometer satellite-modeled data set for the period from 1998 to 2005. Refer to NREL (2011) for additional details and data sources. The white outline defines the approximate composite ranges of Agassiz's (west of the Colorado River) and Morafka's (east of the Colorado River) desert tortoises (Murphy et al. 2011) in the United States, both species of significant conservation concern. This figure was prepared by the National Renewable Energy Laboratory for the US Department of Energy (NREL 2011). The image was authored by an employee of the Alliance for Sustainable Energy, LLC, under Contract no. DE-AC36-08GO28308 with the US Department of Energy. Reprinted with permission from NREL 2011.

Table 1. List of known and potential impacts of utility-scale solar energy development on wildlife in the desert Southwest.

Impacts due to facility construction and decommissioning	Impacts due to facility presence, operation, and maintenance
Destruction and modification of wildlife habitat	Habitat fragmentation and barriers to movement and gene flow
Direct mortality of wildlife	Noise effects
Dust and dust-suppression effects	Electromagnetic field effects
Road effects	Microclimate effects
Off-site impacts	Pollution effects from spills
Destruction and modification of wildlife habitat	Water consumption effects
	Fire effects
	Light pollution effects, including polarized light
	Habitat fragmentation and barriers to movement and gene flow
	Noise effects

Management] -administered lands… and to ensure consistent application of measures to avoid, minimize, or mitigate the adverse impacts of such development" (p. ES-2). As of February 2010, the BLM had 127 active applications for solar facilities on lands that the BLM administers. According to USDOI and USDOE (2011a), all of the BLM-administered land in six states (California, Arizona, Utah, Nevada, New Mexico, and Colorado) was considered initially, for a total of 178 million hectares (ha). Not all of that land is compatible with solar energy development, so three alternative configurations are listed by USDOI and USDOI (2011a) for consideration, ranging from 274,244 to 39,972,558 ha. The larger figure is listed under the *no action alternative* where BLM would continue to use existing policy and guidance to evaluate applications. Of the area being considered under the two action alternatives, approximately 9 million ha meet the criteria established under the BLM's preferred action alternative to support solar development. Twenty-five criteria were used to exclude certain areas of public land from solar development and include environmental, social, and economic factors. The preferred alternative also included the identification of proposed *solar energy zones* (SEZs), defined as "area[s] with few impediments to utility-scale production of solar energy" (USDOI and USDOE 2011a, p. ES-7). By themselves, these SEZs constitute the nonpreferred action alternative of 274,244 ha listed above. Maps of SEZs are available at *http://solareis.anl.gov/documents/dpeis/index.cfm*.

Several sensitive, threatened, or endangered species are being considered within the EIS, but Agassiz's desert tortoise is one of only four species noted whose very presence at a site may be sufficient to exclude USSED in special cases (see table ES.2-2 in USDOI and USDOE 2011a). The potential effects of USSEDO are not trivial for tortoises or other wildlife species. Within the area covered in the draft EIS by USDOI and USDOE (2011a), it is estimated that approximately 161,943 ha of Agassiz's desert tortoise habitat will be directly affected. However, when including direct and indirect impacts on habitat (excluding transmission lines and roads that would add additional impacts; see Lovich and Bainbridge 1999, Kristan and Boarman 2007), it is estimated that approximately 769,230 ha will be affected. Some SEZs are adjacent to critical habitat designated for the recovery of Agassiz's desert tortoise, and this proximity is considered part of the indirect impacts.

On 28 October 2011, while this paper was in press, the BLM and US Department of Energy released a supplement to the EIS (USDOI and USDOE 2011b, 2011c) after receiving more than 80,500 comments. The no action alternative remains the same as in the EIS. The new preferred alternative (slightly reduced to 8,225,179 ha as the modified program alternative) eliminates or adjusts SEZs (now reduced to 115,335 ha in 17 zones as the modified SEZ alternative) to ensure that they are not in high-conflict areas and provides incentives for their use. The new plan also proposes a process to accommodate additional solar energy development outside of SEZs and to revisit ongoing state-based planning efforts to allow consideration of additional SEZs in the future.

The impacts of USSED on wildlife: Effects due to construction and decommissioning

The construction and eventual decommissioning of solar energy facilities will have impacts on wildlife, including rare and endangered species, and on their habitats in the desert (Harte and Jassby 1978). These activities involve significant ground disturbance and direct (e.g., mortality) and indirect (e.g., habitat loss, degradation, modification) impacts on wildlife and their habitat (Kuvlesky et al. 2007). Solar energy facilities require large land areas to harness sunlight and convert it to electrical energy. According to Wilshire and colleagues (2008), photovoltaic panels with a 10% conversion efficiency would need to cover an area of about 32,000 square kilometers, or an area a little smaller than the state of Maryland, to meet the current electricity demands of the United States. Many of the areas being considered for the development of solar energy in the Mojave and Sonoran Deserts are, at present, relatively undisturbed (USDOI and USDOE 2011a).

The extent of surface disturbance of USSED is related to the cooling technology used. Because of the scarcity of water in the desert Southwest region, dry-cooling systems, which consume 90%–95% less water than wet-cooling systems (EPRI 2002), are becoming a more viable option for concentrating solar facilities. Although wet-cooling systems are more economical and efficient, they consume larger amounts of water per kilowatt-hour (Torcellini et al. 2003). Unlike wet-cooling systems, dry-cooling systems use ambient air, instead of water, to cool the exhaust steam from the turbines. However, to achieve a heat-rejection efficiency similar to that in a wet-cooling system, Khalil and colleagues (2006) estimated that a direct dry-cooling system will require a larger footprint and would thus affect more wildlife habitat.

Although we found no information in the scientific literature about the direct effects of USSED on wildlife, the ground-disturbance impacts are expected to be similar to those caused by other human activities in the desert (Lovich and Bainbridge 1999).

Dust and dust suppressants. USSED transforms the landscape substantially through site preparation, including the construction of roads and other infrastructure. In addition, many solar facilities require vegetation removal and grading. These construction activities produce dust emissions, especially in arid environments (Munson et al. 2011), which already have the potential for natural dust emission. Dust can have dramatic effects on ecological processes at all scales (reviewed by Field et al. 2010). At the smallest scale, wind erosion, which powers dust emission, can alter the fertility and water-retention capabilities of the soil. Physiologically, dust can adversely influence the gas exchange, photosynthesis, and water usage of Mojave Desert shrubs (Sharifi et al. 1997). Depending on particle size, wind speed, and other factors, dust emission can physically damage plant species through root exposure, burial, and abrasions to their leaves and stems. The physiological and physical damage to plant species inflicted by dust emissions could ultimately reduce the plants' primary production and could indirectly affect wildlife food plants and habitat quality.

From an operational perspective, dust particles reduce mirror and panel efficiency in converting solar energy into heat or electricity. To combat dust, solar energy facilities apply various dust suppressants to surfaces with exposed soil (e.g., graded areas, areas with vegetation removed, roads). There are eight categories of common dust suppressants used for industrial applications: water, salts and brines, organic nonpetroleum products, synthetic polymers, organic petroleum, electrochemical substances, clay additives, and mulch and fiber mixtures (reviewed in Piechota et al. 2004). In a study conducted in the Mojave Desert in which the hydrological impacts of dust suppressants were compared, Singh and colleagues (2003) reported that changes did occur in the volume, rate, and timing of runoff when dust suppressants were used. In particular, petroleum-based and acrylic-polymer dust suppressants drastically influenced the hydrology of disturbed areas by increasing runoff volume and changing its timing. When it is applied to disturbed desert soils, magnesium chloride ($MgCl_2$), a commonly used salt-based dust depressant, does not increase runoff volume but does, however, increase the total suspended solids loads in runoff (Singh et al. 2003).

Others have highlighted the fact that there is a dearth of scientific research and literature on the effects of dust suppressants on wildlife, including the most commonly used category of dust depressant: brines and salts (Piechota et al. 2004, Goodrich et al. 2008). However, the application of $MgCl_2$ to roads was correlated with a higher frequency of plant damage (Goodrich et al. 2008). Because chloride salts, including $MgCl_2$, are not confined to the point of application but have the ability to be transported in runoff (White and Broadly 2001), the potential exists for a loss of primary production associated with plant damage in the habitats surrounding a solar facility, which could directly affect wildlife habitat.

Mortality of wildlife. We are not aware of any published studies documenting the direct effects of USSED on the survival of wildlife. However, subterranean animals can be affected by USSED, including species that hibernate underground. In the Sonoran Desert portion of California, Cowles (1941) observed that most reptiles in the Coachella Valley hibernated at depths of less than 33 centimeters (cm), with many at considerably shallower depths. Included in his observations were flat-tailed horned lizards (*Phrynosoma mcallii*)—a species of special concern in the region because of solar energy development (USDOI and USDOE 2011a)—and the federally protected Coachella Valley fringe-toed lizard (*Uma inornata*). Even lightweight vehicles like motorcycles are capable of causing greatly increased soil density (soil compaction) at a depth of 30–60 cm as their tires pass over the surface (Webb 1983). These observations suggest that vehicular activities in the desert have the potential to kill or entrap large numbers of subterranean animals (Stebbins 1995) through compressive forces or burrow collapse. Similar or greater impacts would be expected from the heavy equipment associated with the construction activities at an energy facility.

Destruction and modification of wildlife habitat. Despite the absence of published, peer-reviewed information on the effects of USSED on wildlife and their habitats, a considerable body of literature exists on the effects of other ground-disturbing activities on both ecological patterns and processes that are broadly comparable. Ground-disturbing activities affect a variety of processes in the desert, including soil density, water infiltration rate, vulnerability to erosion, secondary plant succession, invasion by exotic plant species, and stability of cryptobiotic soil crusts (for reviews, see Lovich and Bainbridge 1999, Webb et al. 2009). All of these processes have the ability—individually and together—to alter habitat quality, often to the detriment of wildlife. Any disturbance and alteration to the desert landscape, including the construction and decommissioning of utility-scale solar energy facilities, has the potential to increase soil erosion. Erosion can physically and physiologically affect plant species and can thus adversely influence primary production (Sharifi et al. 1997, Field et al. 2010) and food availability for wildlife.

Solar energy facilities require substantial site preparation (including the removal of vegetation) that alters topography and, thus, drainage patterns to divert the surface flow associated with rainfall away from facility infrastructure (Abbasi and Abbasi 2000). Channeling runoff away from plant communities can have dramatic negative effects on water availability and habitat quality in the desert, as was shown by Schlesinger and colleagues (1989). Areas deprived of runoff from sheet flow support less biomass of perennial and annual plants relative to adjacent areas with uninterrupted water-flow patterns.

The impacts of roads. Roads are required in order to provide access to solar energy infrastructure. Both paved and unpaved roads have well-documented negative effects on wildlife (Forman and Alexander 1998), and similar effects are expected in utility-scale solar energy facilities. Although road mortality is most easily detected on the actual roadway, the effects of roads extend far beyond their physical surface. In a study of the effects of roads on Agassiz's desert tortoise populations in southern Nevada, von Seckendorff Hoff and Marlow (2002) examined transects along roads with traffic volumes varying from 25 to 5000 vehicles per day. Tortoises and tortoise sign (e.g., burrows, shells, scat) decreased with their proximity to a road. On roads with high traffic volumes, tortoises and tortoise sign were reduced as far as 4000 meters from the roadside. Roads with lower traffic volumes had fewer far-reaching effects.

Another effect of roads in the desert is the edge enhancement of plants and arthropod herbivores (Lightfoot and Whitford 1991). Perennial plants along the roadside are often larger than those farther away, and annual plant germination is often greatest along the shoulders of roads. It is possible that increased runoff due to impervious pavement or compacted soil contributes to this heterogeneity of vegetation in relationship to a road. Agassiz's desert tortoises may select locations for burrow construction that are close to roads, perhaps because of this increased productivity of food plants (Lovich and Daniels 2000). Although this situation suggests potentially beneficial impacts for herbivorous species of wildlife, such as tortoises, it increases their chance of being killed by vehicle strikes, as was shown by von Seckendorff Hoff and Marlow (2002).

Off-site impacts. Direct impacts on wildlife and habitat can occur well outside the actual footprint of the energy facility. Extraction of large amounts of raw materials for the construction of solar energy facilities (e.g., aggregate, cement, steel, glass); transportation and processing of those materials; the need for large amounts of water for cooling some installations; and the potential for the production of toxic wastes, including coolants, antifreeze, rust inhibitors, and heavy metals, can affect wildlife adjacent to or far from the location of the facility (Abbasi and Abbasi 2000). Abbasi and Abbasi (2000) summarized data suggesting that the material requirements for large-scale solar facilities exceed those for conventional fossil-fuel plants on a cost-per-unit-of-energy basis. In addition, water used for steam production at one solar energy facility in the Mojave Desert of California contained selenium, and the wastewater was pumped into evaporation ponds that attracted birds that fed on invertebrates. Although selenium toxicity was not considered a threat on the basis of the results of one study, the possibility exists for harmful bioaccumulation of this toxic micronutrient (Herbst 2006). In recognition of the hazard, Pimentel and colleagues (1994) suggested that fencing should be used to keep wildlife away from these toxic ponds.

The impacts of USSED on wildlife: Effects due to operation and maintenance

This category includes the effects related to the presence and operation of the solar facility, not the physical construction and decommissioning of the same. Some of the effects (e.g., mortality of wildlife and impacts caused by roads) are similar to those discussed previously for construction and decommissioning and are not discussed further.

Habitat fragmentation. Until relatively recently, the desert Southwest was characterized by large blocks of continuous and interconnected habitat. Roads and urban development continue to contribute to habitat fragmentation in this landscape. Large-scale energy development has the potential to add to and exacerbate the situation, presenting potential barriers to movement and genetic exchange in wildlife populations, including those of bighorn sheep (*Ovis canadensis*), deer (*Odocoileus* spp.), tortoises, and other species of concern and social significance. Research conducted on the effects of oil and gas exploration and development (OGED) on wildlife in the Intermountain West provides a possible analog to USSEDO, since comparable data are not available for the desert Southwest. The potential effects on mule deer (*Odocoileus hemionus*) and other wildlife species include impediments to free movement, the creation of migration bottlenecks, and a reduction in effective winter range size. Mule deer responded immediately to OGED by moving away from disturbances, with no sign of acclimation during the three years of study by Sawyer and colleagues (2009). Some deer avoidance resulted in their use of less-preferred and presumably less-suitable habitats.

Despite a lack of data on the direct contributions of USSEDO to habitat fragmentation, USSEDO has the potential to be an impediment to gene flow for some species. Although the extent of this impact is, as yet, largely unquantified in the desert, compelling evidence for the effects of human-caused habitat fragmentation on diverse wildlife species has already been demonstrated in the adjacent coastal region of southern California (Delaney et al. 2010).

Noise effects. Industrial noise can have impacts on wildlife, including changes to their habitat use and activity patterns, increases in stress, weakened immune systems, reduced reproductive success, altered foraging behavior, increased predation risk, degraded communication with conspecifics, and damaged hearing (Barber et al. 2009, Pater et al. 2009). Changes in sound level of only a few decibels can elicit substantial animal responses. Most noise associated with USSEDO is likely to be generated during the construction phase (Suter 2002), but noise can also be produced during operation and maintenance activities. Brattstrom and Bondello (1983) documented the effects of noise on Mojave

Desert wildlife on the basis of experiments involving off-highway vehicles. Noise from some of these vehicles can reach 110 decibels—near the threshold of human pain and certainly within the range expected for various construction, operation, and maintenance activities (Suter 2002) associated with USSEDO. This level of noise caused hearing loss in animals, such as kangaroo rats (*Dipodomys* spp.), desert iguanas (*Dipsosaurus dorsalis*), and fringe-toed lizards (*Uma* spp.). In addition, it interfered with the ability of kangaroo rats to detect predators, such as rattlesnakes (*Crotalus* spp.), and caused an unnatural emergence of aestivating spadefoot toads (*Scaphiopus* spp.), which would most likely result in their deaths. Because of impacts on wildlife, Brattstrom and Bondello (1983) recommended that "all undisturbed desert habitats, critical habitats, and all ranges of threatened, endangered, or otherwise protected desert species" (p. 204) should be protected from loud noise.

Although many consider solar energy production a "quiet" endeavor, noise is associated with their operation. For example, facilities at which wet-cooling systems are used will have noises generated by fans and pumps. As for facilities with dry-cooling systems, only noise from fans will be produced during operation (EPRI 2002). Because of the larger size requirements of dry-cooling systems, there will be more noise production associated with an increase in the number of fans.

Electromagnetic field generation. When electricity is passed through cables, it generates electric and magnetic fields. USSEDO requires a large distribution system of buried and overhead cables to transmit energy from the point of production to the end user. Electromagnetic fields (EMFs) produced as energy flows through system cables are a concern from the standpoint of both human and wildlife health, yet little information is available to assess the potential impact of the EMFs associated with USSEDO on wildlife. Concerns about EMFs have persisted for a long time, in part because of controversy over whether they're the actual cause of problems and disagreement about the underlying mechanisms for possible effects. For example, there is presently a lack of widely accepted agreement about the biological mechanisms that can explain the consistent associations between extremely low-frequency EMF exposure from overhead power lines and childhood leukemia, although there is no shortage of theories (Gee 2009).

Some conclude that the effects of EMFs on wildlife will be minor because of reviews of the often conflicting and inconclusive literature on the topic (Petersen and Malm 2006). Others suggest that EMFs are a possible source of harm for diverse species of wildlife and contribute to the decline of some mammal populations. Balmori (2010) listed possible impacts of chronic exposure to athermal electromagnetic radiation, which included damage to the nervous system, disruption of circadian rhythm, changes in heart function, impairment of immunity and fertility, and genetic and developmental problems. He concluded that enough evidence exists to confirm harm to wildlife but suggested that further study is urgently needed. Other authors suggest that the generally inconsistent epidemiological evidence in support of the effects of EMFs should not be cause for inaction. Instead, they argue that the precautionary principle should be applied in order to prevent a recurrence of the "late lessons from early warnings" scenario that has been repeated throughout history (Gee 2009).

Magnetic information is used for orientation by diverse species, from insects (Sharma and Kumar 2010) to reptiles (Perry A et al. 1985). Despite recognition of this phenomenon, the direct effects of USSEDO-produced EMFs on wildlife orientation remains unknown.

Microclimate effects. The alteration of a landscape through the removal of vegetation and the construction of structures by humans not only has the potential of increasing animal mortality but also changes the characteristics of the environment in a way that affects wildlife. The potential for microclimate effects unique to solar facilities was discussed by Pimentel and colleagues (1994) and by Harte and Jassby (1978). It has been estimated that a concentrating solar facility can increase the albedo of a desert environment by 30%–56%, which could influence local temperature and precipitation patterns through changes in wind speed and evapotranspiration. Depending on their design, large concentrating solar facilities may also have the ability to produce significant amounts of unused heat that could be carried downwind into adjacent wildlife habitat with the potential to create localized drought conditions. The heat produced by central-tower solar facilities can burn or incinerate birds and flying insects as they pass through the concentrated beams of reflected light (McCrary et al. 1986, Pimentel et al. 1994, Tsoutsos et al. 2005, Wilshire et al. 2008).

A dry-cooled solar facility—in particular, one with a concentrating-trough system—could reject heated air from the cooling process with temperatures 25–35 degrees Fahrenheit higher than the ambient temperature (EPRI 2002). This could affect the microclimate on site or those in adjacent habitats. To our knowledge, no research is available to assess the effects of USSEDO on temperature or that of any other climatic variable on wildlife. However, organisms whose sex is determined by incubation temperatures, such as both species of desert tortoises, may be especially sensitive to temperature changes, because small temperature changes have the potential to alter hatchling sex ratios (Hulin et al. 2009).

Pollutants from spills. USSEDO, especially at wet-cooled solar facilities, has a potential risk for hazardous chemical spills on site, associated with the toxicants used in cooling systems, antifreeze agents, rust inhibitors, herbicides, and heavy metals (Abbasi and Abbasi 2000, Tsoutsos et al. 2005). Wet-cooling solar systems must use treatment chemicals (e.g., chlorine, bromine, selenium) and acids and bases (e.g., sulfuric acid, sodium hydroxide, hydrated lime) for the prevention of fouling and scaling and for pH control of the water used in their recirculating systems (EPRI 2002).

Solar facilities at which a recirculating system is used also have treatment and disposal issues associated with water discharge, known as *blowdown*, which is water with a high concentration of dissolved and suspended materials created by the numerous evaporation cycles in the closed system (EPRI 2002). These discharges may contain chemicals used to prevent fouling and scaling. The potentially tainted water is usually stored in evaporative ponds, which further concentrates the toxicants (Herbst 2006). Because water is an attraction for desert wildlife, numerous species could be adversely affected. The adverse effects of the aforementioned substances and similar ones on wildlife are well documented in the literature, and a full review is outside the scope of this article. However, with the decreased likelihood of wet-cooling systems for solar facilities in the desert, the risk of hazardous spills and discharges on site will be less in the future, because dry-cooling systems eliminate most of the associated water-treatment processes (EPRI 2002). However, there are still risks of spills associated with a dry-cooling system. More research is needed on the adverse effects of chemical spills and tainted-water discharges specifically related to USSEDO on wildlife.

Water consumption (wet-cooled solar). The southwestern United States is a water-poor region, and water use is highly regulated throughout the area. Because of this water limitation, the type of cooling systems installed at solar facilities is limited as well. For example, a once-through cooling system—a form of wet cooling—is generally not feasible in arid environments, because there are few permanent bodies of water (i.e., rivers, oceans, and lakes) from which to draw cool water and then into which to release hot water. Likewise, other wet-cooling options, such as recirculating systems and hybrid systems, are becoming less popular because of water shortage issues in the arid region. Therefore, the popularity of the less-efficient and less-economical dry-cooling systems is increasing on public lands. Water will also be needed at solar facilities to periodically wash dust from the mirrors or panels. Although there are numerous reports in which the costs and benefits were compared both environmentally and economically (EPRI 2002, Khalil et al. 2006) between wet- and dry-cooled solar facilities, to our knowledge no one has actually quantified the effects of water use and consumption on desert wildlife in relation to the operation of these facilities.

Fire risks. Any system that produces electricity and heat has a potential risk of fire, and renewable energy facilities are no exception. Concentrating solar energy facilities harness the sun's energy to heat oils, gases, or liquid sodium, depending on the system design (e.g., heliostat power, trough, dish). With temperatures reaching more than 300 degrees Celsius in most concentrated solar systems, spills and leaks from the coolant system increase the risk of fires (Tsoutsos et al. 2005). Even though all vegetation is usually removed from the site during construction, which reduces the risk of a fire propagating on and off site, the increase of human activity in a desert region increases the potential for fire, especially along major highways and in the densely populated western Mojave Desert (Brooks and Matchett 2006).

The Southwest deserts are not fire-adapted ecosystems: fire was historically uncommon in these regions (Brooks and Esque 2002). However, with the establishment of numerous flammable invasive annual plants in the desert Southwest (Brown and Minnich 1986), coupled with an increase in anthropogenic ignitions, fire has become more common in the deserts, which adversely affects wildlife (Esque et al. 2003). For Agassiz's desert tortoise, fire can translate into direct mortality at renewable energy facilities (Lovich and Daniels 2000) and can cause reductions in food and habitat quality. To our knowledge, however, there is no scientific literature related to the effects of USSEDO-caused fire on wildlife.

Light pollution. Two types of light pollution could be produced by solar energy facilities: ecological light pollution (ELP; Longcore and Rich 2004) and polarized light pollution (PLP; Horváth et al. 2009). The latter, PLP, could be produced at high levels at facilities using photovoltaic solar panels, because dark surfaces polarize light. ELP can also be produced at solar facilities in the form of reflected light. The reflected light from USSEDO has been suggested as a possible hazard to eyesight (Abbasi and Abbasi 2000). ELP could adversely affect the physiology, behavior, and population ecology of wildlife, which could include the alteration of predation, competition, and reproduction (for reviews, see Longcore and Rich 2004, Perry G et al. 2008). For example, the foraging behavior of some species can be adversely affected by light pollution (for a review, see Longcore and Rich 2004). The literature is limited regarding the impact of artificial lighting on amphibians and reptiles (Perry G et al. 2008), and, to our knowledge, there are no published studies in which the impacts on wildlife of light pollution produced by USSEDO have been assessed. However, light pollution is considered by G. Perry and colleagues (2008) to be a serious threat to reptiles, amphibians, and entire ecological communities that requires consideration during project planning. G. Perry and colleagues (2008) further recommended the removal of unnecessary lighting so that the lighting conditions of nearby habitats would be as close as possible to their natural state.

Numerous anthropogenic products—usually those that are dark in color (e.g., oil spills, glass panes, automobiles, plastics, paints, asphalt roads)—can unnaturally polarize light, which can have adverse effects on wildlife (for a review, see Horváth et al. 2009). For example, numerous animal species use polarized light for orientation and navigation purposes (Horváth and Varjú 2004). Therefore, the potential exists for PLP to disrupt the orientation and migration abilities of desert wildlife, including those of sensitive species. In the review by Horváth and colleagues (2009), which was focused mostly on insects but included a few avian references, they highlighted the fact that anthropogenic products that produce PLP can appear to be water bodies to wildlife and can become ecological traps for insects and, to a lesser degree, avian species. Therefore, utility-scale solar energy facilities at which photovoltaic technology is used in the desert Southwest could create a direct effect on insects (i.e., ecological trap), which could have profound but unquantified effects on the ecological community surrounding the solar facility. In addition, there may be indirect effects on wildlife through the limitation of plant food resources, especially if pollinators are negatively affected. As was stated by Horváth and colleagues (2009), the population- and community-level effects of PLP can only be speculated on because of the paucity of data.

Unanswered questions and research needs

In our review of the peer-reviewed scientific literature, we found only one peer-reviewed publication on the specific effects of utility-scale solar energy facility operation on wildlife (McCrary et al. 1986) and none on utility-scale solar energy facility construction or decommissioning. Although it is possible that we missed other peer-reviewed publications, our preliminary assessment demonstrates that very little critically reviewed information is available on this topic. The dearth of published, peer-reviewed scientific information provides an opportunity to identify the fundamental research questions for which resource managers need answers. Without those answers, resource managers will be unable to effectively minimize the negative effects of USSEDO on wildlife, especially before permitting widespread development of this technology on relatively undisturbed public land.

Before-and-after studies. Carefully controlled studies are required in order to tease out the direct and indirect effects of USSEDO on wildlife. Pre- and postconstruction evaluations are necessary to identify the effects of renewable energy facilities and to compare results across studies (Kunz et al. 2007). In their review of wind energy development and wildlife, with an emphasis on birds, Kuvlesky and colleagues (2007) noted that experimental designs and data-collection standards were typically inconsistent among studies. This fact alone contributes measurably to the reported variability among studies or renders comparisons difficult, if not impossible. Additional studies should emphasize the need for carefully controlled before-after-control-impact (BACI) studies (Kuvlesky et al. 2007) with replication (if possible) and a detailed description of site conditions. The potential payoff for supporting BACI studies now could be significant: They could provide answers for how to mitigate the negative impacts on wildlife in a cost-effective and timely manner.

What are the cumulative effects of large numbers of dispersed or concentrated energy facilities? Large portions of the desert Southwest have the potential for solar energy development. Although certain areas are targeted for large facilities because of resource availability and engineering requirements (e.g., their proximity to existing transmission corridors), other areas may receive smaller, more widely scattered facilities. A major unanswered question is what the cumulative impacts of these facilities on wildlife are. Would it be better for wildlife if development is concentrated or if it is scattered in smaller, dispersed facilities? Modeling based on existing data would be highly suspect because of the deficiency of detailed site-level published information identified in our analysis. Except for those on habitat destruction and alteration related to other human endeavors, there are no published articles on the population genetic consequences of habitat fragmentation related to USSED, which makes this a high priority for future research.

What density or design of development maximizes energy benefits while minimizing negative effects on wildlife? We are not aware of any published peer-reviewed studies in which the impacts on wildlife of different USSED densities or designs have been assessed. For example, would it benefit wildlife to leave strips of undisturbed habitat between rows of concentrating solar arrays? Research projects in which various densities, arrays, or designs of energy-development infrastructure are considered would be extremely valuable. BACI studies would be very useful for addressing this deficiency.

What are the best sites for energy farms with respect to the needs of wildlife? The large areas of public land available for renewable energy development in the desert Southwest encompass a wide variety of habitats. Although this provides a large number of choices for USSED, not all areas have the same energy potential because of resource availability and the limitations associated with engineering requirements, as was noted above. Detailed information on wildlife distribution and habitat requirements are crucially needed for proper site location and for the design of renewable energy developments (Tsoutsos et al. 2005). Public-resource-management agencies have access to rich geospatial data sets based on many years of inventories and resource-management planning. These data could be used to identify areas of high value for both energy development and wildlife. Areas with overlapping high values could be carefully studied through risk assessment when it appears that conflicts are likely. Previously degraded wildlife habitats, such as old mine sites, overgrazed pastures, and abandoned crop fields, may be good places to concentrate USSED to minimize its impacts on wildlife (CBI 2010).

Can the impacts of solar energy development on wildlife be mitigated? The construction of solar energy facilities can cause direct mortality of wildlife. In addition, building these facilities results in the destruction and fragmentation of wildlife habitat and may increase the possibility of fire, as was discussed above. Beyond these effects, essentially nothing is known about the operational effects of solar energy facilities on wildlife. Current mitigation strategies for desert tortoises and other protected species include few alternatives other than translocation of the animals from the footprint of the development into other areas. Although this strategy may be appealing at first glance, animal translocation has a checkered history of success, especially for reptiles and amphibians (Germano and Bishop 2008, CBI 2010). Translocation has yet to be demonstrated as a viable long-term solution that would mitigate the destruction of Agassiz's desert tortoise habitat (Ernst and Lovich 2009, CBI 2010).

Conclusions

All energy production has associated social and environmental costs (Budnitz and Holdren 1976, Bezdek 1993). In their review of the adverse environmental effects of renewable energy development, Abbasi and Abbasi (2000) stated that "renewable energy sources are not the panacea they are popularly perceived to be; indeed, in some cases, their adverse environmental impacts can be as strongly negative as the impacts of conventional energy sources" (p. 121). Therefore, responsible, efficient energy production requires both the minimization of environmental costs and the maximization of benefits to society—factors that are not mutually exclusive. Stevens and colleagues (1991) and Martín-López and colleagues (2008) suggested that the analyses of costs and benefits should include both wildlife use and existence values. On the basis of our review of the existing peer-reviewed scientific literature, it appears that insufficient evidence is available to determine whether solar energy development, as it is envisioned for the desert Southwest, is compatible with wildlife conservation. This is especially true for threatened species such as Agassiz's desert tortoise. The many other unanswered questions that remain after reviewing the available evidence provide opportunities for future research, as was outlined above.

The shift toward renewable energy is widely perceived by the public as a "green movement" intended to reduce greenhouse-gas emissions and acid rain and to curb global climate change (Abbasi and Abbasi 2000). However, as was noted by Harte and Jassby (1978), just because an energy technology is simple, thermodynamically optimal, renewable, or inexpensive does not mean that it will be benign from an ecological perspective. The issue of wildlife impacts is much more complex than is widely appreciated, especially when the various scales of impact (e.g., local, regional, global) are considered. Our analysis shows that, on a local scale, so little is known about the effects USSEDO on wildlife that extrapolation to larger scales with any degree of confidence is currently limited by an inadequate amount of scientific data. Therefore, without additional research to fill the significant information void, accurate assessment of the potential impacts of solar energy development on wildlife is largely theoretical but needs to be empirical and well-founded on supporting science.

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