International Journal of Engineering and Science Invention (IJESI)
ISSN (Online): 2319-6734, ISSN (Print): 2319-6726
www.ijesi.org ||Volume 13 Issue 5 May 2024 || PP 21-50

Outdoor Noise and its Mitigation

S. David Graber P.E.
Consulting Engineer, Stoughton, Massachusetts, USA

Abstract: *The focus of this paper is on outdoor noise as distinct from control of noise in indoor spaces. Historical reports of outdoor noises and more recent related observations are discussed. Sound propagation, hearing, and health effects are addressed. Additional topics are noise regulations, noise impacts of and mitigation for wastewater treatment facilities, sound insulation, and noise barriers. Noise levels and physical damage of blasting and control methods are addressed. Cavitation is addressed with the focus on noise. There is further discussion of silencers for centrifugal dynamic blowers and rotary positive-displacement blowers. Pile driving can be a significant cause of complaints; alternatives and mitigation are addressed. Numerous miscellaneous noise sources are addressed. Effects of construction and operation of facilities on property values are discussed. along with compensatory mitigation.*

Keywords: *Ambient noise; Noise control; Noise regulations; Sound propagation; Wastewater treatment facilities*

Date of Submission: 11-05-2024 Date of Acceptance: 23-05-2024

I. Introduction

"What kind of noise annoys an oyster?" A song of that title was composed and sung by Frank Crumit in 1930, and has become a mantra of acoustic engineers. It reflects the subjective nature of annoyance with regard to noise. An example of this was seen by the author when he was called upon as an expert witness in a case involving an attempt by the City of Revere, Massachusetts, USA to take by eminent domain Rowe Quarry for construction of a shopping center. Operation of this granite quarry began in the year 1880. The quarry owners successfully fought the egregious misuse of the eminent domain attempt. The quarry reached the end of its useful life, the land was sold, and the quarry filled in 2002 after about 120 years of use. Most pertinent to the present subject is the author's observation that several times a day a loud warning siren signaled an upcoming blast and the blast itself was very loud. Families living in company housing took this entirely in stride because their families' livelihoods depended on the quarry operation. Blasting annoyance and mitigation are discussed further in a later section on **Blasting.**

The focus here is on outdoor noise as distinct from control of noise in indoor spaces such as can be important for engine generator and blower rooms and other areas of wastewater treatment facilities. The purpose is to exemplify mitigation measures and add some perspective. Topics discussed are under the headings of Historical Reports and More Recent Related Observations; Sound Propagation, Hearing, and Health Effects; Noise Regulations; Wastewater Treatment Facilities; Sound Insulation; Noise Barriers; Blasting; Cavitation; Silencers; Piling Driving; Miscellaneous Noise Sources; and Property Values.

II. Historical Reports and More Recent Related Observations

There are some interesting historical reports of outdoor noises. One reference discovered and cited by the author [1] pertains to the Indus River in Pakistan. Postel and Richter [2] note that the Indus no longer reaches the sea for most months of the year, with adverse effects on delta ecosystems. However, an account by Wood [3] suggests that the bore was present there in 1836. In January 1837, Wood, in a condescending, colonial-era manner, describes the area around the Indus and an event which he witnessed on an unnamed date in the previous year (1836). The steamer on which he was traveling had just moored in the evening below the village of Rattí on the eastern shore of the Indus opposite present-day Thatta (the site of an ancient city referred to by Wood as T'hat'hah):" [t]he steamer had moored just below the village when, at about seven o'clock in the evening, we were startled by a loud continuous noise, like the rush of falling water or the rolling of distant thunder. The up-heaving of the river and quick heavy roll of the vessel told us that part of the bank had given way. Before the water could regain its level another and another mass fell into the stream. We landed and surveyed the scene. Since sunset a great alteration had taken place in the bank of the river....The people are...accustomed to these visitations."

Present-day or historic (extinct) tidal bores occur on China's Qiantang River (see the author's photograph on Figure 1 below), the Shubenacadie and other rivers flowing into Canada's Bay of Fundy, England's Humber Estuary, Alaska's Knik Arm and Turnagain Arm, Brazil's Amazon River, the Colorado River in the Southwestern United States and northern Mexico, France's Seine River and Mont-Saint-Michel Bay, England's Severn and Trent Rivers, Scotland's Solway Firth, the Bamu River in New Guinea, the Indus River in Pakistan, and India's Hugli River. The bore has the fascinating appearance of current from upstream and downstream conspicuously coming into each other along a line approximately perpendicular to the shore; on the upriver side of the bore the tidal current goes out and on the downriver side the tidal current comes in (or goes out at a lower speed, depending on the freshwater flow), with an abrupt change in the tidal velocity across the bore.

None of the records of tidal bores and related cultural interactions approach those for the Qiantang River, which has been famous for its tidal bore, and related legends, poetry, science, engineering, and history for more than a thousand years. In the 1700s (Qian Long period of Qing Dynasty), the so-called "fish-scale" stone embankment was constructed, although construction on a Qiantang River embankment is thought to date back to around 100 CE (construction started as far back as the Han Dynasty and lasted until the Qing Dynasty). The embankment of the Qiantang River is considered one of the three great ancient engineering feats in China, alongside the Great Wall and the Grand Canal that connects Beijing and Hangzhou. Chanson [4] described the tidal bore on China's Qiantang River when crashing into the side platform with loud and powerful noises on October 12, 2014, with the bore height of about 3 m (10 ft).

Eight iron oxen were also placed on the Qiantang River bank near the village of Haining to provide mythical protection against the assaults of the bore. However, they weren't able to protect themselves. The power of the Qiantang tidal bore is evidenced by the fact that the eight iron oxen, 1.5 tons each, were washed away in 1953. Figure 2 shows photographs of the two replica replacements. After the bore has passed, local shipping travelling upstream benefits from the strong current. But the ships must avoid being damaged by the bore. One means of dealing with the oncoming bore is for ships to ground themselves on platforms provided for that purpose. Figure 3 shows a portion of the platform and a portion of the embankment as the bore is passing.

The bore is not always of dramatic height. In the night of June 7, 2002, although too dark to see, the author could hear the loud roar of the tidal bore well upstream on the Shubenacadie River in Nova Scotia from a nearby cabin. However, the following morning the author observed the bore from a boat on the River at Anthony's Nose, nearer the River's mouth. At that time and location it was little more than a few inches high and only made a sizzling sound.

Another interesting feature of the tidal bore is that it does not reverse and head back out in a seaward direction. Graber [5] applied the Second Law of Thermodynamics and concept of entropy to provide the reason for this.

Waterfalls provide another interesting example. James Prescott Joule, a pioneer in the field of thermodynamics, is also known for a famous story that during his honeymoon he measured the differences in water temperature at the top and bottom of a waterfall [6]. Joule attempted to demonstrate that water at the bottom of a waterfall should be warmer than water at the top. That is a reasonable expectation since kinetic energy would be converted to heat. It would be expected to be partially converted to noise as well, and such a conversion was the subject of a study by Al-Musawi [7]. Al-Musawi measured sound spectra for both laboratory and field waterfalls. The flow rates were only measured for the laboratory waterfalls, but the sound levels were found to be similar for field waterfalls and some of the laboratory ones.

Quantitative results of waterfall noise measurements were provided by Lilly [8] for cascading and free falling (plunge) waterfalls and indoor and outdoor man-made waterfalls. He found that waterfall noise is greatest in the free fall configuration, that the sound level is independent of height if it exceeds 3 feet (due to breakup of the plunging water into discontinuous flows), and that the overall noise level is dependent only on the volumetric flow rate. Lilly gives the most abundant noise measurements for the free falling Snoqualmie Falls in the State of Washington, with a drop of 267 feet. A USGS gaging station provided daily mean discharges. The photograph below (Figure 4) was taken when the flow rate was 862 cfs on July 25, 2007. Another photograph in Lilly [8] shows water cascading over the full width of the falls with a flow rate of 23,700 cfs on January 13, 2003.

Figure 1. Tidal bore of about 1 meter (3 ft) on the Qiantang River, Haining, China, October 20, 2010 (photograph by author)

Figure 2. Replica Replacement of Protective Iron Oxen along the Qiantang River, Haining, China, October 20, 2010 (photograph by author)

Figure 3. Ship Grounding Platform and Tidal Bore on the Qiantang River, Haining, China, October 20, 2010 (photograph by author)

Figure 4. Snoqualmie Falls (after Lilly 2007)

A document by The Howes Family Association gives a quote and reference regarding an event in connection with Thomas Howes that surely affected many others as well. "On June first, 1638, an earthquake caused considerable damage to property and alarm to people and lasted for about four minutes, and was followed by less severe shocks during the succeeding weeks."

“The morning of Friday, June 1, 1638, was very pleasant. The sun shone brightly, and the wind came gently from the west. The month of roses never opened more auspiciously….Noon came and passed, and the settlers proceeded to their various labors in the field. Between one and two o'clock acute ears heard a low murmur of distant sound, which grew louder and clearer until everyone heard what seemed to be the rumble of thunder far away. In a minute or two it increased in volume and in sharpness until it resembled the rattling of many carriages fiercely driven over granite pavements. The people were startled by the noise and discontinued the work upon which they were engaged to discover whence the sound came, and what it was. A clear sky beamed down upon them. Not a cloud could be seen out of which the thunder tones could emanate. The more they thought of the matter, the greater grew their perplexity. Not many moments elapsed, however, before the earth began to tremble beneath their feet, and terrified they threw down their tools and ran reeling like drunken men, with ghastly countenances, to the first group of people they could find, for men like many animals will flock together when they are afraid. The shaking of the earth increased to such a violent extent that people could not stand erect without supporting themselves by taking hold of posts or palings and other fixtures. Not only the mainland, but the islands in the ocean were shaken violently, and the vessels that rode in the harbors and those sailing along the coast were acted upon as if a series of tidal waves had passed under them….People in their houses were much alarmed, for not only did they hear the awful sound and feel the trembling of the earth, but the houses over them shook to their very foundations, and it seemed as if they must collapse. The chimneys of the first houses here were built on the outside at the ends of the houses, with the tops rising just above the roof. They were massive piles of rough and uneven stones, generally some six feet square, the sides being nearly perpendicular. Imperfectly built, without mortar except for filling, they readily yielded to the terrible shaking they received, and the tops of many of them fell off, striking on the house or on the ground. The noise of the falling stones outside accompanied the rattle of pewter platters and dishes and other things that stood upon the shelves in the houses, which knocked against each other and fell down….This first and greatest shock of the earthquake continued for about four minutes. It came from the western and uninhabited portion of the country and proceeded easterly into the Atlantic. It shook the whole country from the coast into the wilderness for many miles, the Indians reporting that they felt it far in the interior….The first shock died away and the noised [sic] ceased. The people began to resume their several labors. Half an hour passed, when to their surprise and terror, the horrible rumbling of the thunderous sound, and the quaking of the earth were renewed. But it quickly passed, being less violent than the first shock. For twenty days the earth was in an unquiet condition….Some of the people of Plymouth were about to remove to another place, and several of the principal persons of the town were gathered at a house for an hour of conference before their separation. While thus engaged, the terrible noise and shaking of the earth came upon them. The men were sitting in the house talking together, and some women and others were without the door. Those outside would have been thrown to the ground if they had not caught hold of the posts and pales near which they were standing….At Newbury, a town meeting was in progress, and while the questions which arose for decision were being discussed, the sound of the on-coming earthquake burst upon their ears, as the historian says, like ‘a shrill clap of thunder.’ The building was violently shaken; and wonder and amazement and fear filled the minds of the people. After the tumult had ceased, before proceeding into further business, the assembly voted to record the fact of the earthquake, concluding their record thus, ‘wherefore taking notice of so great and strange a hand of God's providence, we were desirous of leaving it on record to the view of after ages to the intent that all might take notice of Almighty God and fear this name.’….Earthquakes are always fearful and impressive, but the people of the time when this one occurred must have had many doubts and fears in their minds. They were not only superstitious, but this was a new and unknown world, which but a few years before was pictured with the most awful terrors….This, the greatest earthquake of the seventeenth century, marked an epoch in the lives of the settlers of New England, and for many year[s] afterwards it was common for them to compute dates of incidents as ‘so long since the earthquake.’” [9] **N.B.**: Although the earthquake occurred on 11 June 1638, this article lists the earthquake as having occurred on 1 June 1638. This time discrepancy is due to the change from the Julian to Gregorian calendar.” [10].

III. Sound Propagation, Hearing, and Health Effects

Sound Propagation

Linda Greenlaw’s book “All Fishermen are Liars” [11] itemizes the following sailors’ sayings regarding sound propagation:

‘’’When boat horns sound hollow, rain will surely follow.’’ The atmospheric conditions and height of cloud cover, if any, affect the way the sound of a ship’s horn travels and its tonal quality.”’
“”Sound traveling far and wide a stormy day does like betide.” Similar to the…[above]. This may suggest that you can hear bad weather approaching.”’

There are technical bases for these sayings which will become evident below. Sound propagation calculations should consider: (1) divergence, (2) atmospheric absorption under particular conditions of temperature and relative humidity, (3) channeling, and (4) barrier attenuation. Other forms of attenuation (e.g., ground absorption [12], excess anomalous attenuation [13]) are neglected because they are not reliable over the range of meteorological conditions and frequencies. Piercy and Embleton [14] demonstrated this for ground absorption., For excess anomalous attenuation, in 1988 Kurze and Beranek [15, §7.8] presented various data, the upshot of which is that this is not a reliable form of attenuation.

The first three of the considerations enumerated in the previous paragraph are discussed in the present section and the fourth is discussed under **Noise Barriers** below. The calculations should be based on sound pressure levels properly measured for similar equipment at an appropriate reference distance (and height) for the proposed equipment (and which the manufacturers are willing to guarantee),

Sound divergence occurs as the sound power becomes spread over a larger area causing the sound intensity to decrease. When the noise source is close to the ground, as is the most common case, the divergence is hemispherical. Hemispherical divergence of sound waves is calculated according to $20\log_{10}(R/R_{ref})$ in which R_{ref} is the reference distance referred to above and R is the distance from the proposed unit to the location of concern.

The atmosphere absorbs sound as sound vibrations are transferred to molecular motion of the air. Atmospheric absorption in a function of sound frequency, air temperature, and humidity. In northern climates, atmospheric sound absorption should be based on the American National Standards Institute standard entitled "Method for the Calculation of the Absorption of Sound by the Atmosphere, ANSI S1.26-1978" [16], at a temperature of 0 degrees C and relative humidity of 100 percent for conservatism. The corresponding atmospheric absorption values are as follows (dB/100 m):

Octave Band Center Frequency – Hz

31.5	63	125	250	500	1000	2000	4000	8000
0	0.01	0.03	0.08	0.14	0.32	0.99	3.52	12.13

Or in dB/1000 ft:

Octave Band Center Frequency – Hz

31.5	63	125	250	500	1000	2000	4000	8000
0	0	0.1	0.2	0.4	1.0	3.0	10.7	37.0

In warmer climates, lower temperatures can be assumed as appropriate.

An example for a diesel engine on the Deer Island (Boston, Massachusetts, USA) Water Pollution Control Facility will be started here, then built on later with a noise barrier. The diesel engine has a dominant casing sound level at 500 Hz frequency of 82 dB at 50 ft. The elevation of the source is 135.0 ft and of the receiver at the Winthrop Town line is 115.0 ft. The horizontal distance between those two locations is 1,800 ft. The straight line distance from source to receiver is $\sqrt{(1800)^2+(20)^2} = 1800.11$ ft. The hemispherical divergence is $20\log_{10}(R/R_{ref}) = 20\log_{10}(1800.11/50) = 31.13$ dB. From the tabulation above, the atmospheric absorption at 500 Hz is 0.4 Hz/1000 ft x 1800.11/1000 = 0.72 dB. The receptor sound level is thus 82 – 31.13 – 0.72 = 50.15 dB.

It is sometimes suggested (e.g., for the Recycling Center discussed below) that a wooded buffer zone may help reduce noise transmission. Such a buffer would be important visually. However, foliage usually has a negligible effect on sound transmission, except for high frequencies and at large distances [14].

Anderson and Kurze in Beranek and Ver’s Noise and Vibration Control Engineering [17] note that “channeling” over water can result in sound levels being 10-20 dBA (“A”-weighted decibels) higher than would otherwise be expected. They imply that channeling is a daytime phenomenon, because it is the combination of wind direction and temperature inversion (which is disrupted at night) that causes the downward bending of sound waves at the top of the “channel”.

Hearing

The human ear varies in its sensitivity to different frequencies of sound. Except for sounds of a single frequency (see "pure tones" defined below), sounds generally have multiple frequencies. The ear responds differently to different frequencies, some being perceived as louder than others. To have a single sound metric that represents the human perception of loudness, the "A-weighted" scale has been devised and incorporated in the functioning of noise meters (other metrics are defined where they first appear). The unit of sound at a single frequency is the decibel, denoted dB. The A-weighted unit is denoted dBA. The decibel scale is devised such that 0 dB is the lowest decibel that most humans can hear. In some exceptional cases, humans can hear sounds down to -15 dB. 0 dB sounds are very soft and barely perceptible by the human ear. To understand just how soft, a whisper is about 30 dB and 30 dB is 1,000 times louder than a 3 dB sound [because $\log_{10}(10^{30} - 10^{3}) = 27 \cong 30$]. Human ears can detect an incredibly wide range of sounds. Sound intensity is measured on a logarithmic base 10 scale, which proceeds in multiples of 10, rather than a linear scale because the ears response to sound intensity appears to be logarithmic. (The Richter scale of earthquake intensity is another example of a logarithmic scale.)

The sensitivity of human hearing is generally restricted to the frequency range of 20 Hz to 20,000 Hz. The human ear, however, is most sensitive to sound in the 500 to 8,000 Hz frequency range. Above and below this range, the ear becomes progressively less sensitive. To account for this feature of human hearing, sound level meters incorporate a filtering of acoustic signals according to frequency. This filtering is devised to correspond to the varying sensitivity of the human ear to sound over the audible frequency range. This filtering is called A-weighting. Sound pressure level values obtained using this weighting are referred to as A-weighted sound pressure levels and are signified by the identifier dBA. To provide some perspective, some A-weighted sound pressure levels of various common sounds are: 30 dBA for a soft whisper at 2 ft, 60 dBA for normal conversational speech at 5 ft – 10 ft, 70 dBA for an air compressor at 50 ft, 80 dBA for a diesel locomotive at 50 ft, 100 dBA for an automobile horn at 10 ft, 120 dBA for jet aircraft takeoff at 100 ft, and 130 dBA threshold of pain. For continuous sound, an increment or decrease in sound pressure level by 3 dB or less is barely perceptive, an increase or decrease of 5 dB is clearly perceptive, an increase or decrease of 10 dB is perceived as a doubling or halving of noise level. Beranek [18] discussed the damage to the hear caused by noise. General discussions of the harmful physiological and psychological effects of noise are given by Cohen [19] and Berdik [20] and in Reference [21, Section 3]..

Health Effects

"Noise can damage more than just your ears." A range of adverse health effects are now known to be associated with noise. These include heart disease, diabetes, impaired vision, high blood pressure, impeded blood circulation, learning problems, and stroke. [22, 23]

IV. Noise Regulations

Problematic Noise Regulations

The author will here discuss problematic noise regulations, then give an example of improved regulations prepared by the author. The Massachusetts Department of Environmental Protection (MDEP) has noise regulations given in its Code of Massachusetts Regulations (CMR) at 310 CMR The regulations are enforced by the MDEP Division of Air Quality Control, aided by its Form DDS-8: Design Data Sheet for Equipment Generating Noise. It specifies a 10 dBA limit as an increase that applies only to operating noise. There is no State noise limit applicable to construction noise. Form DDS-8 defines "ambient" as the "background" A-weighted sound pressure level that is exceeded 90% of the time measured during equipment operating hours (unless established by other means with the consent of the Department). The Data Sheet also prohibits a "pure tone" condition, defined as a condition in which "any octave band center frequency sound pressure level exceeds the two adjacent center frequency sound pressure levels by 3 decibels or more."

There are two major inadequacies of the MDEP noise regulations. First, the allowed 10 dBA increase is excessive. A 10 dBA increase is perceived as a doubling of noise levels [24] . Such an increase, particularly if it is from a continuous (e.g., operating) noise source and especially if occurs at night, could have a severe impact. A second major inadequacy is the reference to an exceedance above a vaguely defined "background" noise level. That vagueness could allow the following to occur. An industrial facility can come to a quiet neighborhood and cause a 10 dBA exceedance, and comply with the MDEP regulations. The proponent of a second facility can then argue that the background noise level is now that with the first industrial facility operating, and add 10 dBA to that "background". An expansion of the first facility can then add another 10 dBA using similar reasoning. And then the proponent of the second facility can propose to expand it and add another 10 dBA. The result in such a situation would be four 10 dBA increases above the original background, each of which represents a doubling of perceived noise level. Although a hypothetical example, numerically speaking, this sequence of events is precisely what has occurred and continues to occur in other Massachusetts locations.

(An example is given below for Salem, Massachusetts.) In this manner it is possible for project proponents to compound exceedance upon exceedance in a way that can result in a noise level that is grossly unacceptable by any other reasonable standard. Such a clearly absurd situation would not be allowed by regulations, as found in other jurisdictions, which have absolute (rather than relative) standards.

However, not all absolute noise standards are reasonable. For example, Department of Housing and Urban Development (HUD) Noise Abatement and Control standards [25,26,27] give as an "Acceptable" standard a Day-night average sound level (in decibels) as "Not exceeding 65 dB." Under certain specified circumstances, higher noise levels are allowed with "Special Approvals." The "stick" is prohibition of HUD support for new construction. These noise levels would be excessive in many locations.

It should also be noted that it cannot be assured that attainment with the Massachusetts regulations, limited as they are, will be realized. As an example, in the same Salem neighborhood referred to above residents have complained about the noise from odor-control equipment installed during the summer of 1991 at a wastewater treatment plant. The existence of a puretone from that equipment was documented in formal comments provided by the author under the Massachusetts Environmental Policy Act (MEPA). Subsequent research found that the required MEPA process was neither followed nor required by MDEP for that installation, which became the subject of a law suit by the City of Salem in Essex County Superior Court. More broadly in this regard, it is important to understand that that any "commitments" under the MEPA process, such as in the Facilities Plant/Environmental Impact Report (FP/EIR), are "informational" and do not have the force of law. It is therefore important that mitigation commitments be incorporated in a legally-binding Memorandum of Understanding between the parties. An example of this is given below for Salem, Massachusetts, USA.

Another example of a serious puretone violation was in connection with odor-control fans installed at the Massachusetts Water Resources Authority (MWRA) Boston Harbor Sludge Processing Facility at Fore River in Quincy, Massachusetts, USA [28].. A Memorandum of Understanding (MOU) between Quincy and MWRA was the primary force moving that violation to an acceptable resolution. That MOU was adopted with minor changes from the Winthrop/MWRA MOU negotiated by the author and discussed below.

DEP's inability to monitor compliance with its puretone regulations is reflected by the fact that the Air Quality Section Chief at the Lakeville District of DEP informed the author that the agency did not even have noise meters with which octave band measurements (necessary for detection of puretones) can be made.

In the U.S. in 1981, the Reagan administration essentially dismantled the Federal 1972 noise-control program, by conniving to enact weak legislation that basically preempted local standards without adding effective alternative standards [29]. In addition, Reagan, in 1982, eliminated the Environmental Protection Agency's Office of Noise Abatement and Control [30, 31]. One humorous account in the just-cited reference is that of an angry Bavarian who mounted a catapult in his front yard and launched his wife's homemade dumplings at low-flying jet fighters from a nearby military base. A comprehensive discussion of noise effects on health, quality of life, and preemption is provided in an excellent *Consumer Reports* article [32].

Improved Noise Regulations

In establishing noise regulations, variations in noise levels need to be understood. In some locations, and perhaps most, day-by day variations in ambient noise levels can be substantial. This can be due to coastal wave action, atmospheric conditions carrying distant noise more effectively, wind, rain, and other factors. The higher ambient levels may consist of incoherent "white noise" that is not perceived as noise in the sense of being unwanted sound. And, the higher the ambient levels can mask noise that would otherwise be bothersome. A good example was the old diesel pump engines at Deer Island discussed below, which could not be heard many nights but, when running in the exact same way, could be quite bothersome on other nights.

If measurements of ambient noise levels are made over too short a period of time, such as just one day, then the quieter periods may not be observed. Then designing source noise controls to avoid excessively exceeding the observed ambient may result in noticeable noise and complaints at times when the ambient noise level is lower. In some locations, the ambient sound pressure level that is exceeded 90% of the time (known as the L_{90}) can vary significantly from day to day. And that variation may not be detected by a few short-term measurements. It is the lower ambient levels that are more important for purposes of assessing potential noise impacts. Their determination may require noise measurements over an extended period. For the Deer Island facilities, measurements were made continuously over a period of weeks, and the 90-percentile L_{90} was decided upon as a suitable ambient.

Some good examples of the above were observed during the pre-construction noise measurements in the vicinity of the Highpoint Quincy construction site discussed below. Ambient (L_{90}) sound levels varied substantially at the residential noise monitoring locations from night to night (and from location to location). For example, the midnight ambient sound levels at one residential location varied over a range of 16 dBA from night to night over the five-day monitoring period. If only one night had been monitored, then a high, unrepresentative, ambient noise level might have been accepted. A the author's suggestion the city required as nighttime ambient levels the minimum hourly values at the quietest location; those values were significantly lower than the proponent's proposal. The minimum such value, occurring at 3:00 am was 32 dBA.

The author prepared noise regulations that were enacted by the Town of Winthrop, Massachusetts, USA under the authority granted in Chapter 40, Section 21 of the General Laws of the Commonwealth of Massachusetts. Major features of those regulations are detailed below. There is a DEFINITIONS section at the end of the regulations, but those terms are generally self-explanatory.

Regulation 1: General Prohibition of Noise Emissions – No person or persons owning, leasing, or controlling the operation of any source or sources of noise shall willingly, negligently, or through failure to provide necessary equipment or facilities or to take necessary precautions, permit the establishment of a condition of noise pollution.

2.5 Zoning District Noise Standards

Noise standards referred to in these Regulations for the several zoning districts…, as defined in and established pursuant to the Winthrop zoning bylaws, are as established by the following table:

TABLE OF ZONING DISTRICT NOISE STANDARDS

Maximum Allowable Sound Pressure Levels – dBA

Residential or Conservation		Business	Light Manufacturing
Daytime	All Other Times	Anytime	Anytime
45 dBA	35 dBA	65 dBA	70 dBA

Subsequent sections of the regulations include enforcement and fines, restrict noise emitted from construction sites, noise emitted from motor vehicles, noise emitted from outdoor powered equipment, and noise emitted from acoustical devices and musical instruments. The latter is a wide-spread problem; a Florida state law [33] deals specifically with the problem of "ear-splitting tooth-rattling speakers booming from [a] vehicle…." A newspaper article [34] about Rutland, Vermont, USA states that officials there were considering a law to regulate car stereo noise that was described as "so loud that the cannon-fire thud of the bass rattles the windows of stores and homes as they cruise the streets."

Winthrop also has regulations pertaining to boating noise (CHAPTER 19 – TOWN BEACHES AND BOATING): Unmuffled noise from engines, both inboard and outboard, and all amplifying systems, radios and similar devices shall be controlled and reduced to minimum volume when in the vicinity at a distance of one hundred yards from any pier, floats or yacht anchorage and Town Landing.

The role of Conservation Commissions in Massachusetts is described in Section IX below. In the present context, Winthrop issued an Order of Conditions for a project involving restoration of the Winthrop Shores Reservation to which the author contributed noise-control provisions: "That noise shall be controlled in compliance with the Town of Winthrop's noise regulations." "In view of the fact that certain construction will be carried out 24 hours per day, seven days per week, in close proximity to Winthrop residences, and with major potential to have adverse impacts, the WCC considers it important that noise…be adequately mitigated. The plans for such mitigation…shall be submitted at least one month prior to commencement of construction. Those plans shall be submitted to the WCC for review by the WCC and others in Winthrop and approval by the WCC." Furthermore, the project was designated as "major construction" under Winthrop's Noise Control Regulations, with the project proponent being advised in writing that focus would be placed on modifications to equipment back-up alarms, vehicle mufflers, and pneumatic exhaust silencers.

Our focus is on community rather than occupational noise standards. However, brief mention is made here of occupational noise exposure. The importance of that subject is evidenced by the Center for Disease Control (CDC) stating that 22 million workers are exposed to potentially damaging noise at work each year; such occupational hearing loss is preventable. [35] The Occupational Safety and Health Act of 1970 (Public Law 91-596) charged the National Institute for Occupational Safety and Health (NIOSH) with recommending occupational safety and health standards and describing hearing exposure concentrations that are safe for various periods of employment, including diminished hearing and other effects. NIOSH communicates those recommended standards to regulatory agencies, including the Occupational Safety and Health Administration (OSHA) and to others in the occupational safety and health community.

V. Wastewater Treatment Facilities

Winthrop, Massachusetts

The Deer Island Water Pollution Control Facility serves 43 municipalities in Eastern Massachusetts, USA and is the second largest such plant in the United States. It is adjacent to the Town of Winthrop, Massachusetts on which it historically had major adverse impacts. Due to pollution of Boston Harbor caused in large part by that facility, in the year 1985 a federal lawsuit was brought by the Conservation Law Foundation and the U.S. Environmental Protection Agency and joined by the Town of Winthrop and City of Quincy, Massachusetts. The legal aspects of this case are addressed in Dolin [36]. Consequently, the facility came under federal court order, and the Massachusetts Water Resources Authority was created pursuant to that order. The author then was engaged by the Town of Winthrop and thence provided extensive consulting services over a 16-year period reviewing all aspects of the facility design and operation to mitigate impacts on the Town and simultaneously advised the MWRA on design details. Funding for the author's reviews was provided originally by the MWRA by direct reimbursement to Winthrop, and subsequently to Winthrop by nondiscretionary funding provided by MWRA.

One of the first issues the author addressed was noise impacts. There was a physician who lived in Point Shirley (the nearest location in Winthrop to Deer Island) who would make his point about an annoying operating noise on the Island by imitating with great skill the throbbing sound of the large Nordberg diesel-driven pumps in the main pumping station on Deer Island. In addition to the noise problem, the diesel exhaust had stack fires and spewed oil which accumulated on the roof of the pumping station and caught fire on numerous occasions. The Winthrop Fire Department, as the first responder to Deer Island, had many fire hoses that had to be discarded because of oil fouling when fighting the roof fires (a factor that led the author to successfully obtaining an agreement that the Winthrop Fire Department would receive $250,000 in annual payments from MWRA). The author worked with MWRA and its consultant to achieve a resolution to the diesel noise problem, an incidental part of which entailed bringing a power cable from Boston Edison across Boston Harbor to Deer Island to serve as a source of power to the plant while the diesels were being repaired. Testing of two of the diesels on February 24, 1988 in the critical 63 Hz octave band at 3 feet horizontally from the center of the exhaust stack showed peak levels of 117 and 125 dB. Subsequently, responding to Winthrop's concerns, the stacks and silencers were replaced. An interesting aspect of that was that, working with MWRA's acoustical consultant, silencers were specified that had characteristics which exceeded the performance of off-the-shelf units. The manufacturer (Burgess-Manning, Inc., Buffalo, New York, USA) was able to design and provide units that met those specifications. Similar testing on March 21, 1990 on two of the diesels after the silencers were replaced showed reduction to 100 dB or less, indicating a noise reduction in the range of 17 to 25 dB at 63 Hz. Similar results were found for four of the diesels on February 28, 1991. Those levels were no longer audible in Winthrop. As part of the subsequent upgrading of the treatment facility, the Nordberg diesels were replaced with new diesel engines.

Excellent studies and recommendations regarding noise control at the Deer Island Wastewater Treatment Plant (WWTP) were presented by Bradley, *et al*. [37], [38], [39]. Time has enabled demonstration of the success of the long-term noise mitigation efforts.

Memorandum of Understanding (MOU)

MWRA had made major commitments to environmental mitigation measures through the federal and state environmental review processes. Why then a formal Memorandum of Understanding [40]? That was partly because of additional issues and greater specificity desired. And also because the Massachusetts Environmental Policy Act produces non-binding policy documents in which the mitigation is often implemented to the extent the impacted parties are vigilant and even then not necessarily. Furthermore, the National Environmental Policy Act is only as effective as the U.S. Environmental Protection Agency chooses to enforce their Record of Determination and has the leverage to do so via federal grants. Relevant portions of the MOU signed February 12, 1988 are given below.

SECTION I. ENVIRONMENTAL MITIGATION

…

C. Noise Control

(1) Noise associated with the operation of the facility shall conform to the following:
   (a) Night-time (7:00 pm to 7:00 am) noise transmitted to the Town line from the facility shall not exceed 36 dBA so that when combined with a 36 dBA ambient, the noise level will not exceed 39 dBA.
   (b) Daytime (7:00 am to 7:00 pm) noise transmitted to the Town line from the facility shall not exceed 36 dBA.

(2) Noise associated with the construction of the facility shall conform to the following:
  (a) Nigh-time as set forth in (1)(a) above.
  (b) Weekday daytime noise at the Winthrop/Deer Island line will conform to the noise profiles found in [a prescribed document]….
  (c) Except for the possibility indicated in (d) below, daytime noise on weekends and federal holidays shall be as set forth in (1)(a) above.
  (d) The parties recognize the possibility of Saturday morning construction. The MWRA will undertake aa detailed assessment of the noise impacts to establish these needs and to meet the Court schedule. Upon completion of that assessment, the parties will agree to a resolution which may include jointly petitioning the court for extension of its milestones or extending weekday hours of construction. Should Saturday morning construction be demonstrated to be necessary, an appropriate noise level will be established.

An interesting occurrence was during the transport of concrete by truck through Winthrop for construction of on-island piers. The time it took for such transport through the Town resulted in the concrete almost setting up and being barely usable. So MWRA decided to construct a concrete batch plant on Deer Island. Then it was decided to convey concrete ingredients (cement, sand, gravel) by barge to the on-island piers. Although MWRA referred to these as mitigation measures, they were actually logistical necessities.

Other provisions of the MOU dealt with reduction of traffic noise, e.g., by converting from trucking of chlorine gas to Deer Island to the barging of sodium hypochlorite for disinfection (II.D); maintaining a specified separation area of berms and open space between the constructed facilities and the Town to mitigate noise and odor impacts (I.E); and a related enforcement procedure (I.F).

Some Interesting Winthrop History

The roadway on the peninsula connecting Winthrop to Deer Island has an interesting history [41]. Despite its name, Deer Island was once an island, but now is not an island at all. It is a peninsula connected to the Town of Winthrop. In colonial times Shirley Gut, which separated the island and the mainland, was a respectable 325 feet across—wide enough to allow the frigate USS Constitution, "Old Ironsides", to steal out to sea to escape British blockaders during the War of 1812. Deer Island remained intact until a 1938 hurricane filled Shirley Gut with sand. In 1942, the U.S. Army build Fort Dawes on the island and constructed a road across the former Shirley Gut waterway. Storms continued to throw sand and rocks onto the peninsula, cutting off access. When a storm was expected, the Winthrop Fire Department would station a fire company on the Island To remediate that situation, MWRA planned to construct an improved roadway and a seawall on the harbor side. The author worked closely with MWRA on the design of that seawall. Because that construction was adjacent to the Winthrop Town Line and extended into Winthrop, MOU noise limits could not be achieved. Through close coordination with the author, noise level criteria and mitigation measures were developed which were acceptable to the Town and not prohibitive to the contractor.

Salem, Massachusetts

The author was brought in by the Town of Salem, Massachusetts in connection with the upgrading of the South Essex Sewerage District (SESD) regional wastewater treatment plant in Salem, which services the Massachusetts communities of Beverly, Danvers, Marblehead, Peabody and Salem. Discharge is to Salem Sound which flows to the Atlantic Ocean.. Noise from the existing facility, together with a coal-fired power plant, was a major problem for nearby residents.

The problem discussed under **IV. Noise Regulations -** ***Problematic Noise Regulations*** of compounding exceedances was particularly applicable to the Salem project. Initially a quiet neighborhood, the Salem Harbor Power Plant, constructed in the 1950s and expanded numerous times, took up most of the 10 dBA allotment. Subsequently the regional primary wastewater treatment plant in Salem, adjacent to the power plant, used the new baseline established by the power plant to add another 10 dBA, establishing a new baseline. An expansion of the power plant then added another 10 dBA to that baseline. Subsequently, the proponents of an upgraded secondary treatment plant proposed to use another 10 dBA allotment. The result in this situation would be four 10 dBA increases above the original background, each of which represents a doubling of the perceived noise level.

The author questioned the adequacy of noise measurements by the facility's consultant, and brought in his own expert who found major faults with those measurements, and performed independent noise measurements. Based on that work and the arguments presented in the previous paragraph, SESD concluded that it would be more economical for the District to purchase the nearby homes. A Memorandum of Understanding was negotiated by the author between Salem and the South Essex Sanitary District requiring such purchases, and that was done.

Salem, New Hampshire

The author was brought in by the Town of Salem, New Hampshire in connection with the Greater Lawrence Sanitary District (GLSD) regional wastewater treatment facilities, which services Salem, New Hampshire and the Massachusetts municipalities of Lawrence, Methuen, North Andover, Andover, and Dracut. Discharge is to the Merrimack River, which .flows ultimately to the Gulf of Maine. The District's acoustical consultant characterized ambient noise levels based on two 8-minute samples, one daytime and the other night-time. At a meeting with the design engineer, the author suggested that this was not an adequate characterization, and further took issue with the manner in which day-night average sound levels (L_{dn}) were calculated. (L_{dn} refers to the day-night average sound level defined as the average noise level over a 24-hour period.) The L_{dn} values were calculated from L_{90} values whereas they should have been calculated from energy-equivalent sound levels (L_{eq}). Using the L_{dn} values for background noise level and increase in noise level are meaningless. Another acoustical consultant was present and agreed with the author. He suggested more appropriate noise measurements, Although no improved data were provided, most of the noise-producing components were enclosed in concrete structures. Quiet-duty motors were specified, and silencers were installed on all ventilation equipment to reduce fan-intake and exhaust noise levels.

North Andover, Massachusetts

The engagement discussed above occurred during the years 1991-1992. Subsequently, beginning in the year 2000, the author was engaged by the Town of North Andover in connection with GLSD's plans to construct improvement to its wastewater treatment facilities. The proposed improvements included construction of sludge processing facilities, including two gravity belt thickeners, three new anaerobic digesters, a dewatering centrifuge, odor-control technology, heat drying and pelletizing processes, and other ancillary and accessory improvements. The author worked with an attorney on this project. There was jurisdictional litigation regarding the respective regulatory authorities of the Town vs. the District. The Massachusetts Superior Court ruled that the Town had no regulatory authority regarding anti-nuisance conditions. That decision was overturned on appeal by the Massachusetts Supreme Judicial Court on March 30, 2003. More specifically was the matter of whether the Town's Board of Health had the authority to impose numerous conditions of which noise control was one. The matter went back to the local court, whereupon settlement was reached between the parties. Most relevant in the present context were noise provisions embodied in the settlement agreement as follows:

- The improvements shall not individually or cumulatively cause noise to increase at any residence by more than 5 decibels above the ambient levels….The improvement shall not cause a "pure tone" condition as that term is described in air quality policies established by the Massachusetts Department of Environmental Protection. Should the improvements be in violation of the five decibel standard, GLSD may demonstrate that the ambient levels…are not representative of the ambient that existed as of the day(s) of violation.
- Within ninety days from the date of this Agreement, GLSD shall monitor sound levels at…three residential locations…to determine whether the improvements meet the noise criteria set forth in the preceding paragraph. GLSD shall report the results of this monitoring to the Board, and shall take necessary and reasonable actions to reduce sound levels from the improvements if the data demonstrates noncompliance with these criteria.
- Upon request of the Board, GLSD shall monitor sound levels at the three residential locations…on an annual basis, and report the results to the Board. The Board shall not require annual noise monitoring unless there are recurring complaints from multiple sources about noise from the improvements.
- Whenever GLSD is required by permit to notify a regulatory agency of an accident or violation relating to air quality, noise, odor, traffic, or fire safety, GLSD shall also notify the Board of Health at the same time that it notifies the regulatory agency.

The facility has operated successfully in terms of function and impacts [42].

Rockport, Massachusetts

The author provided expert services to Travelers Insurance in connection with litigation concerning the Rockport Wastewater Treatment Plant. The Town filed suit against four defendants prompted primarily by noise complaints by citizens neighboring the plant. Travelers represented Fram Corporation which was one of four defendants named in the case involving noise and other alleged inadequacies of Fram's mechanical aeration equipment. The case was settled favorably for Fram, with the plant's design engineering firm settling for $1,102,000 and agreeing to indemnify the other defendants.

Algonquin Gas Transmission

The Algonquin Gas Transmission was a $30 million 1,100 miles long pipeline system constructed in the years 2003-2004, which delivers natural gas to New England . It is connected to the Texas Eastern Pipeline and the Maritimes & Northeast Pipeline. The Algonquin Gas Transmission pipelines transport about 20 billion cubic meters of natural gas per annum. It generally receives gas that originated in the Gulf of Mexico, although it also receives gas from an LNG terminal in Massachusetts. The author reviewed and commented, on behalf of the City of Quincy, Massachusetts, on the Environmental Impact Report for the portion of the project entailing construction of a 29-mile 30-inch diameter underwater gas transmission line from Beverly, Massachusetts to Quincy, Massachusetts. Primary concerns were construction noise associated with dredging operations and impacts on intertidal clam flats. Fortuitously, changes made to address the latter ameliorated the former. Those changes entailed lengthening the pipeline by approximately 500 feet and extending it northerly away from the clam flats by approximately 225 feet [43]. Additional mitigation measures implemented at the author's request were sequencing work in the Fore River prior to anadromous fish runs, scheduling blasting to avoid the anadromous run of blueback herring in the Fore River, the use of fish startling methods with sound waves to drive fish away from blast zones, and scheduling of dredging to avoid lobster migration.

Federal Guidelines

Under the U.S. Clean Water Act, the Federal Water Quality Administration issued Federal Guidelines for the "Design, Operation and Maintenance of Waste Water Treatment Facilities." VII.j required: "Equipment with high noise levels, such as compressors and centrifuges, shall be enclosed in separate rooms, which should be sufficiently soundproof to the protect the operator and to satisfy neighborhood environmental requirements."

Advocacy

Appropriate ambient noise levels and meaningful noise control objectives are something on which well-meaning experts can disagree. Unfortunately, advocacy at times plays a role in noise control. The author listened as the principal of a major Massachusetts noise consulting firm told his client: "You tell me what noise level you want and I will find a way to predict it."

VI. Sound Insulation

The Point Shirley and Cottage Hill neighborhoods in the Town of Winthrop, Massachusetts, USA experience a severe impact from overflights due to proximity to Logan International Airport. These neighborhoods experience about 20 percent of the overflights daily (an average of about 160 aircraft) with planes at an altitude of less than 500 feet, which results in major noise impacts. The Massachusetts Port Authority (Massport), which owns and operates the airport, presented noise data in 1982 which indicated average" day/night noise levels in the two above-mentioned neighborhoods of 73 and 74 dBA respectively ("indicative of a very noisy urban residential area"). Social surveys have shown that between 25 and 37% of the residents in a community exposed to such noise levels will be "highly annoyed." [44] [45] [46].

In 1985, a program was agreed upon with Massport whereby homes within a prescribed area (from the Deer Island boundary to the L_{dn} 73 contour near the top of Cottage Hill) would be provided with sound insulation and air conditioning of a room of preference. The prescribed area was that from the Deer Island boundary to the "L_{dn}" 73 contour near the top of Cottage Hill. The noise measurements between the hours of 22:00 and 07:00 were artificially increased by 10 dB before averaging. This noise was weighted to take into account the decrease in community background noise of 10 dB during this period. An acoustical testing program was included, with a particular focus on homes for which window replacement was refused in order to determine acoustical effectiveness and allow the homeowner to reconsider if warranted. In 2022, a new program was established by Massport for the upgrading and expansion of the home insulation program [47].

A complementary program was provided by the Town of Winthrop, using $23,450,000 mitigation funding from the Massachusetts Water Resources Authority over a 12-year period. That program, overseen by the author, mitigated noise associated with construction of the Deer Island Water Pollution Control Facility in a defined impacted area. That program provided air conditioning of a room of preference, acoustic ceiling insulation, and insulating window replacement (variously with regular double glass, heat-absorbing double glass, or clear triple glass). The author reviewed the technical submittals in detail and affected significant changes, particularly in the area of sizing of air-conditioning units, including preventing oversizing. Oversizing air-conditioning equipment can cause [48, 49]: higher and less uniform humidity levels, discomfort due to short on-times and wide indoor temperature swings, higher electric current requirements, and higher energy use due to an increase in starting thermal transient losses, stopping thermal transient losses, and off-cycle losses. The need for expensive electrical upgrades can also be required. The sizing of the units was reduced in accordance with the author's review. Of particular significance here is that smaller air conditioning units generate lower levels of noise.

A similar program was provided by the Massachusetts Bay Transit Authority (MBTA) for Scituate, Massachusetts whereby 53 homeowners could receive from $5,000 to $30,000 for noise-reducing home improvements intended to reduce the impact of the Greenbush rail line .With a total cost of $74,000, the funds would be allotted up to $5,000 for each decibel of anticipated noise impact over a specific threshold. The problematic difference between this program and the Massport one was that the homeowners had to pay for the improvements themselves then be reimbursed by the MBTA [50].

Air conditioning was provided for a different reason near the Quarry Hills site in Quincy and Milton, Massachusetts, USA. Because of a serious construction dust problem in the neighboring residential area, the site owner bought and delivered 36 air-conditioning units to those homes and provided 174 car wash sticker books to the residents. The site owner also replaced with granite blocks a wall that fell over due to blasting at Quarry Hills.

VII. Noise Barriers

It should be understood at the outset that the ability of barriers to mitigate noise requires that the noise source be close to the barrier (such as traffic noise barriers, in which the source-to-barrier distance is a small multiple of the of the barrier height) or close to the noise receptors. The ability of a noise barrier to mitigate noise from a large construction site would be limited to receptors close to the barrier.

If barrier attenuation is considered (and the landform barriers are often of minimal significance for Deer Island noise sources), then the Kurze/Schreiber method· [16] [51] should be used. The Kurze/Schreiber method uses a weather correction factor which accounts for conditions that reduce barrier effectiveness. The weather correction is incorporated in a term which is a function only of barrier-source-receiver geometry. The equation for a single barrier in units of dB is as follows:

$$A_{\text{barrier}} = 10\log_{10}\left[3 + 40\left(z/\lambda\right)K_w\right] \quad \ldots(1)$$

$$K_w = \exp\left(-\frac{1}{2000\text{m}}\sqrt{\frac{abs}{2z}}\right) \quad \ldots(2)$$

in which z is the path length difference between diffracted and direct rays (i.e., between a straight line from barrier to receiver and over the barrier), λ is the sound wave length (varies with frequency), K_w is a weather correction factor, 2000m is dimensional 2000 meters, and a, b and s are the line-of-sight distances from source to top of barrier, top of barrier to receiver, and source to receiver, respectively. The path difference is:

$$z = a + b - s\,. \quad \_(3)$$

The barrier height should be properly determined in relation to receptor locations (e.g., the maximum barrier location is not "seen" by all receptor locations). Flanking paths (edge effects) should also be considered to assure that the minimum path length distance is being used; in that case a weather correction is not needed so $K_w = 1$. Related references are [52], [53], and [54].

Noise barriers were proposed for mitigation of noise from several of the Deer Island construction projects. Barrier calculations for the first proposed use of barriers were for Early Site Protection Existing Outfall Protection (April 1988). Those calculations used the Maekawa method [13], the inadequacy of which is discussed below under **VIII. Blasting**. After the author's critique of that method, MWRA' acoustical consultant used the Kurze/Schreiber method for subsequent projects. Despite the acoustical consultant's competent implementation, MWRA's specifications did not always properly include that consultant's recommendations. Those include Disinfection Facilities I/Seawall (CP-204) and (CP-241) Disinfection Facilities II/ Hydroelectric Plant Phase II. Another problem on Deer Island was the failure to recognize the 20 dB upper limit to the effectiveness of noise barriers [52 §5.6]. That was the case for CP-204 and CP-241.

An example of a barrier calculation is given here, building on the example in Section III. A landform on Deer Island was constructed for the main purpose of disposing excavated fill. Secondarily, the landform was vegetated to create an attractive visual barrier and to provide a noise barrier between the island and the Town of Winthrop. Vertical and horizontal dimensions were as follows: Barrier Elevation =165 ft, Source to Barrier = 300 ft, Receiver to Barrier = 1,500 ft, Source Elevation = 135.0 ft, Receiver Elevation = 115 ft, The terms in the equations given above are:

$$a = \sqrt{300^2 + \left(165 - 135\right)^2} = 301.5 \text{ ft} = 91.9 \text{ m}$$

$$b = \sqrt{1500^2 + (165-115)^2} = 1{,}500.8 \text{ ft} = 457.5 \text{ m}$$

$$s = \sqrt{(135-115)^2 + (300+1500)^2} = 1{,}800.1 \text{ ft} = 548.7 \text{ m}$$

$$z = 301.5 + 1500.8 - 1800.1 = 2.2 \text{ ft} = 0.7 \text{ m}$$

$$K_w = \exp\left(-\frac{1}{2000}\sqrt{\frac{91.9(457.5)(548.7)}{2(0.7)}}\right) = 0.1268$$

At 68°F and normal atmospheric pressure of 14.7 psi, speed of sound in air c equals 1128 ft/sec = 344 m/sec. The corresponding sound wave length is given by $\lambda = c/f = 344/f$ with frequency f in Hz. The equation for DLz is:

$$\text{DLz} = 10\log_{10}\left[3 + 40(1)zK_w/(344/f)\right] = 10\log_{10}\left[3 + 40(1)(0.7)(0.1268)/(344/f)\right]$$

The corresponding values of DLz at each octave band center frequency are as follows:

Octave Band Center Frequency – Hz								
31.5	63	125	250	500	1000	2000	4000	8000
_	5.60	6.28	7.40	9.02	11.13	13.61	16.32	19.18

The receptor sound level at 500 Hz is thus 9.02 dB lower than the 50.15 dB value without the barrier, giving the Winthrop Town line noise level 50.15 – 9.02 = 41.13 dB.

The U,S, Environmental Protection Agency required that Deer Island drumlins be excavated from their south side (away from Winthrop) so the remnant acted as a noise barrier. Construction was limited to one shift, daytime operations. Special quiet-wheeled bulldozers were used, supplemented by a mobile crane.

References regarding double barriers give uncertain results. Anderson and Kurze [16] give a ratio which they claim limits the added effectiveness of a second barrier to 5 dB. That ratio contains the variables wavelength λ and separation between variables s. However, calculation of that ratio give values ranging from 3 at λ/s = 0 to a limit of 1 at large λ/s. Piercy and Embleton {14} suggest that "The acoustical design of barriers is largely empirical, both because of the lack of precise theory for even simple barriers and because of the great variety and complexity of acoustical environments at which barriers are used."

.

VIII. Blasting

Blasting is of concern for two reasons in the present context, being noise levels and physical damage to structures. Noise levels are primarily associated with air overpressures. Physical damage can be caused both by air overpressures (such as window damage) and ground vibrations that can damage structures. Both can be startling to those nearby. Sain [55] provides a good discussion of control of blasting to minimize vibration and noise.

Westbury Home Damage

An example of physical damage occurred in Westbury, Massachusetts, USA during construction by the Massachusetts Water Resources Authority (MWRA) of the West Roxbury Tunnel. Three homes there were so severely damaged that the homeowners vacated their homes under a relocation agreement (the homes were purchased by MWRA) and a fourth home had damage that required restoration. "Vibration monitoring and settlement at various locations have been within the allowable tolerances" [56]. The latter speaks to the inadequacy of the monitoring, a topic which is further addressed below.

Highpoint Quincy Construction

Blast noise complaints were reported during construction of the ten-building, 1,040 unit, Highpoint Apartment complex in Quincy, Massachusetts. Ground vibrations were said to have rattled homes and caused property damage [57]. These problems were foreseen in a report by an acoustical consultant [58] and not adequately addressed. One useful provision of Quincy's conditions was that all houses within 300 feet of the site borders received structural surveys prior to rock blasting, unless permission was denied by the owner. A considerable amount of wood clearing was necessary at this site, involving chain sawing and wood chipping. Electric chain saws were used, which have a noise level of about 70 dB versus 100 dB for gasoline chain saws. Wood chippers have a noise level of about 110 dB; a noise mitigation measure at this site was having one or more trailers located between wood chippers and the residential area. Another mitigation measure was locating the stone crushing equipment under an instant-spring structure; such structures are estimated to provide a 33.5 dBA reduction [59].

Noise complaints at this site were surely influenced by the residents' unfavorable disposition related to visual impacts associated with replacing a wooded area with a very visible apartment complex. This is contrary to the Deer Island facility discussed next, where an impactful prison (escapes into the Winthrop community, loud sirens during prison escapes) was being demolished and replaced by a landscaped landform barrier.

Deer Island Water Pollution Control Facility

There were numerous projects during construction of the Deer Island Water Pollution Control Facility that included blasting. Among those were bunker demolition, inter-island shafts and tunnel, and outfall shaft and tunnel. The author worked closely with MWRA and its consultants to develop acceptable specifications and procedures for seismic/noise performance and monitoring. Included were requirements that the raw weekly test data be sent to the author. That was not happening consistently and what data were submitted were clearly erroneous. That was rectified by having MWRA accept the author's suggestion that, rather than the MWRA or their construction manager, their Acoustical Consultant check and furnish the results.

An initial criterion of 90 dBA at the Winthrop Town line was included in the Early Site Preparation contract specifications for blasting on Deer Island. Initial seismic/noise data suggested that most of the measured overpressure spectrum was in the sub-audible range (less than approximately 20 Hz), and that a 120 dB limit at Point Shirley would suffice. That was borne out by further work, and it was concluded that the 120 dB limit at the Town line would serve its intended purpose of reducing air-pressure induced structural/window rattling and also prevent excessive blasting noise. For nighttime blasting a criterion of 108 dB was used, which resulted in minimal complaints.

Monitoring initially consisted of placement at the Town line of a seismic/noise monitor that was set for seismic triggering. However, because the seismic vibrations were not always sufficient to trigger that monitor, no noise data were obtained. To temporarily rectify that, the monitor was manually triggered just before a blast so that noise data would be obtained. However, the meter ranges were not set correctly, so no noise data were recorded. These problems were rectified by: (1) placing a seismically-triggered monitor close to the Town line to measure vibrations at the location and (2) placing a seismic monitor in sufficient proximity to the blast location to insure a triggered, identifiable measurement. For the latter, the blast overpressures were extrapolated to the Town line for comparison to the 120 dB criterion by calculation. The measured overpressure (dB_m) was extrapolated to the Town line based on:

$$dB_m - 20\log_{10}(R_{bt} / R_{bm}) \qquad \text{... (4)}$$

MWRA' noise consultant was initially using the Maekawa attenuation formula [13] and then changed, at the author's suggestion, to the Kurze and Schreiber formulation [17] [51]. The basic issue here is that the Kurze and Schreiber method provides the degree of conservatism (i.e., considers meteorological conditions that favor noise propagation and which will occur a significant portion of the time) that should be applied to such operating noises. The author demonstrated the difference between the two methods by applying them to a diesel exhaust spectrum. The output showed that the Maekawa method predicted a 8 dB lower receptor noise level than the Kurze/Schreiber method.

Looking at this difference in greater detail, there is a built-in inaccuracy in the Maekawa method which stems from the fact that the Maekawa method is a semi-empirical method which included excess anomalous attenuation (discussed above) in the original observations [61]. In the Kurze and Schreiber method the term Dlz includes that excess attenuation, and that excess attenuation is subtracted out (the term Dbm) to obtain the insertion loss alone (De). The Maekawa method fails to make that correction, and hence will give about 5 dB of insertion loss even if there is no barrier! Note the +5 term in the Maekawa equation and its near equality to the value of 4.8 as the subtracted Dbn term.

Although mostly successful, the Deer Island construction noise controls were insufficient in one case: noise from tunnel ventilation fans associated with the shafts mentioned above. Noise from those fans were a persistent source of complaints about which MWRA failed to take responsible action, even though the contractors were in noncompliance with their contract noise limits.

Worthy of mention here is that the Town of Winthrop implemented an additional procedure relative to blasting. That was a Heavy Vehicle Permit process whereby trucks going through Winthrop to Deer Island had to have a Town permit issued in advance. In the case of vehicles transporting explosives, a Winthrop police escort was required. That applied to vehicles carrying explosives to Deer Island and any unused explosives being transported off the island.

Braintree-Weymouth Relief Tunnel

The author was part of a team reviewing plans for the Braintree-Weymouth Sewer Relief Tunnel in Massachusetts, USA. A main feature of the work was constructing a shaft approximately 200 feet deep through 100 feet of soil and 100 feet of rock by drilling and blasting. The shaft provided access for a tunnel boring machine. That machine bored a 2,200-ft tunnel, which connected to a drop shaft that connected to another 9,800 feet of tunnel to Nut Island. The work was done for the Town of Weymouth under a technical assistance grant from the Massachusetts Water Resources Authority. The author's review focused on the mitigation of construction and operating impacts. Project specifications were successfully changed in those areas. Proposed construction-equipment noise levels at 50 feet included one for chain saws of 86 dBA. The author successfully suggested that electric chain saws be used, for which the maximum noise level would be about 69 dBA (per Table B.3 of [60]). Other mitigation measures to which the proponent agreed were that dewatering pumps would be electrically-driven, sheet piles would be installed by vibratory methods rather than by pile drivers, and that blast noise would be monitored in sufficient proximity to the blast location to ensure a triggered, identifiable measurement, with blast noise to be extrapolated from the monitoring location to the property lines at which the blast noise limit applies (using the method described above for Deer Island). For daytime blasting the same 120 dB was used as for the Deer Island work discussed above. For nighttime blasting the same 108 dB criterion was used as mentioned above for Deer Island. The noise criteria in terms of peak overpressures were measured by wide-spectrum meters that measure air pressures not only in the audible range but also the low-frequency pressure waves that are primarily responsible for window rattling and other structural vibrations.

Nut Island Shaft

To complete the connection from the south service area to the Deer Island Water Pollution Control Facility, the relief tunnel discussed just above had to be connected to the inter-island tunnel discussed earlier. That was accomplished by construction of the Nut Island shaft. That shaft was approximately 235 feet deep through 75 feet of soil overburden and 160 feet of bedrock. The author was brought in by an attorney to assist in mitigation of noise during construction and operation, with agreement reached on the following. The shaft was constructed by auger drilling through the soil and raised-bore drilling through the bedrock. Sheet piles were installed by vibratory methods instead of pile driving. All permanent pump-station mechanical equipment was housed within a building oriented to minimize sound impacts to the residential area. All pump station mechanical rooms were void of windows and had acoustical gaskets on doors for sound attenuation. The largest pumps were installed below ground on the lowest level of the building. The pump station included acoustical walls and a hospital (critical) grade silencer for sound attenuation of generator room and exhaust, respectively.

Weymouth Power Plant

Dismantling of Sithe Energy's power plant in Weymouth using blasting and wrecking balls caused damage and noticeable shaking in nearby homes. Unfortunately pre-blast surveys were not required for this site, unlike requirements for the Highpoint site discussed above. Seventy homeowners closest to the plant property were offered vouchers for free interior dust cleaning, power washing of dust-covered home exteriors, and coupons for free car washes [62]. Then, a new company, Exelon Corporation, purchased the site and remaining equipment in the fall of 2002 and began to restore the Weymouth power plant. In the spring of 2003 complaints resumed, due to loud blasts occurring during cleaning of the gas and steam turbines preparatory to opening the plant [63]. The noise got to the point that the mayor ordered a work stoppage for a day and imposed nighttime noise limitations. [64, 65, 66, 67, 68]

Once construction of the plant was completed, the operating noise continued to disturb some residents. The noise levels were once again said to be in compliance with the MDEP regulations discussed above [69]. The problem once again was that the MDEP noise regulations are inadequate as discussed above under ***Problematic Noise Regulations***.

IX. Cavitation

Cavitation is due to reduction of pressure at some point in a system to less than the vapor pressure of water at the prevailing temperature. That vapor pressure is approximately 0.5 psi at normal temperatures. Cavitation is a result of a combination of a high velocity at some point within a hydraulic device (meter, valve, orifice, pump, etc.) and sufficiently low upstream pressure which causes (according to Bernoulli's Theorem or conservation of energy) a sufficiently low pressure at the high velocity location. A subsequent downstream increase in pressure above vapor pressure causes the sudden, implosive elimination of the vapor bubbles, which results in cavitation damage in the form of pitting of pipe walls and appurtenances and attendant noise. Cavitation can also be associated with waterhammer.

Cavitation can produce intense noise. Cavitation in valves is a particular problem in this regard [70]. Ball and Tullis [70] characterized cavitation in butterfly valves in a way that has applicability to all of the devices mentioned above. They considered three cavitation levels:

1. ***Incipient cavitation*** is the stage at which cavitation becomes audible as light intermittent pops.
2. ***Critical cavitation*** is the stage at which cavitation becomes audibly steady (while remaining light).
3. ***Choking cavitation (or supercavitation)*** is the stage of heavy cavitation where the discharge becomes and remains constant for a given upstream pressure irrespective of further decreases in downstream pressure. (Choking is a phenomenon of compressible gas flow, discussed in Section 9.4). Cavitation intensity at the valve is a maximum at this stage.

Between critical and choking cavitation, the degree of cavitation changes from mild (sounding like "pebbles in the line") to severe (sounding like "heavy hammer blows or a loud roar"). Baumann [71] notes valve cavitation not only causes severe damage to valve trim, but also creates sound levels that can exceed 110 dB. Baumann also states that damage is caused when the imploding vapor bubbles create pressure waves that can accelerate at $1.5(10)^{11}$ m/s^2 and reach velocities of 500 m/s. Kurkjian [72] notes that certain research studies have demonstrated forces equivalent to 100,000 psi and higher associated with supercavitation downstream of butterfly valves.

Baumann [71] presents a thorough discussion, to which the reader is referred, of various means of eliminating or reducing throttling-valve cavitation. Some are well-known methods, such as reducing the altitude of the valve or installing two valves in series. Others are newer methods for butterfly valves, such as injecting air into the fluid through a series of holes by using the vacuum pressure created by the cavitating fluid, vane designs using a row of teeth on both leading edges of the valve vane to split up the liquid jets, and a sharktooth butterfly system. The reader is referred to Baumann for details.

Cavitation can cause catastrophic damage. An example, for which the author was hired to determine the cause and recommend protective measures, is for the Spring Street Pumping Station in Arlington, Massachusetts, USA. That station draws water directly from a 56-inch diameter main via 1,400 feet of 36-inch diameter reinforced-concrete pipe. The 36-inch transmission main continues into an elaborate pipe network that services the towns of Arlington, Belmont, Lexington, and Waltham. The system extends out to 15,600 ft from the pumping station. Two storage facilities are in the network: the Arlington Heights Standpipe and the Walnut Hill Elevated Water Tank in Lexington. The station is a component in a system operated by the Massachusetts Water Resources Authority. The Station has three 300-hp pumps and one 150-hp pump. Station discharge is to a 36-inch diameter reinforced-concrete main that feeds the Northern Extra High (NEH) Service Area. The discharge line from each pump is equipped with a control valve. Cone valves were originally installed for this purpose. On April 12, 1994, at approximately 7:15 PM, there was a “catastrophic” break of the discharge piping in the basement of the Spring Street Pumping Station. A substantial length of interconnected water distribution piping ruptured and several homes were flooded. A power failure at the pumping station caused negative pressure waves to travel to a downstream high point where a cavitation pocket formed. The negative waves were reflected from that pocket back to the pump where they were reflected as excessive positive waves which resulted in pipe failure near the pumping station.

The author discovered that the two-million gallon Walnut Hill Elevated Water Tank had been taken out of service for maintenance just before the damage occurred. The author’s analysis demonstrated that that tank provided critical surge control and that its being offline, in conjunction with the concurrent pump operating conditions, led to the failure. The author made detailed recommendations for both physical additions and operating rules to provide adequate system protection. These included checking, and modifying as necessary, standpipe and water tank altitude valve controls to insure that they stay open on power failure; insuring that pump shutdown and startup take place with the altitude valve open to prevent the possibility of the pump tripping with the altitude valve closed; limiting the operation of the Spring Street Pumping Station in a prescribed manner under standpipe or tank out-of-service conditions; and installation of a vacuum relief valve at a specified location.

X. Silencers

Silencers are used on the discharge and/or inlet sides of blowers to reduce noise levels. Their design and selection entails a tradeoff between noise attenuation and pressure drop. Increasing the silencer size to reduce pressure drop increases the exterior surface area of the silencer from which noise is radiated. The internal construction of a chamber-type silencer includes packing (usually hair felt or glass pack) which may be added in combination chamber-absorptive type silencers or may be used with different internal construction for absorption silencers. Combination intake filter-silencers are also available in smaller sizes. Manufacturers' silencer pressure-drop formulae can be reduced to a $KV^2/(2g)$ relationship. Silencer pressure drops often constitute the largest single pressure drop in environmental engineering gas systems, and further research and development oriented toward a standard-production low-pressure-drop silencer seems warranted. The power savings often justify a more expensive silencer. However, there is a tradeoff to be considered between pressure drop and noise, because increasing conventional silencer sizes decreases pressure drop but increases noise.

Blowers are classified as dynamic blowers and rotary positive-displacement blowers. As with dynamic pumps, dynamic blowers may have the flow leave the blower impeller in radial or axial directions, the former being termed centrifugal blowers and the latter axial blowers. Centrifugal blowers are the dominant type of dynamic blower in environmental engineering applications. Their primary use is for the aeration of activated sludge systems. Rotary positive-displacement blowers are used in wastewater treatment plants to supply air for mixing and channel agitation.

Centrifugal Dynamic Blowers

For the 23 mgd Cranston, Rhode Island Wastewater Treatment Plant, the author specified three multistage centrifugal blowers for aeration of activated sludge tanks. Each blower delivers air at a rated capacity of 5400 scfm measured at 14.7 psi absolute, 68 deg F, and 36 percent relative humidity when operating at the following conditions: inlet temperature 97 deg F, inlet pressure at blower flange 14.3 psia, discharge pressure at blower flange 22.2 psia, relative humidity 85 percent, normal barometer 14.7 psia. Each blower is driven by a 300 hp, 3600 rpm squirrel cage induction motor, having sufficient capacity to allow full load blower torque over the range of blower operating conditions. One blower was required to be witness tested according to the ASME Power Test Code for Compressors and Exhausters (PTC 10). Maximum sound levels and noise tests were also specified. Inlet butterfly valves perform the functions of unloading the blower in conjunction with the discharge blow-off valves during startup, and then control the flow through the blower by inlet throttling. At design conditions, the inlet valve is specified to control volume from 100 percent to 50 percent flow, with the blowers remaining stable throughout this range. Inlet throttling is important for this type of blower to prevent surge conditions. Inlet and discharge silencers and noise tests were specified to meet specified sound levels. Maximum sound levels were specified to be 90 dBA as measured by octave band analysis when all blower units are operating simultaneously in the Blower Building. When the relation between the over-all noise level and frequency band analysis of the blowers is known, the over-all noise level as measured by the sound level meter only may be a sufficient alternative to the octave band analysis. This decision will be at the discretion of the Engineer. If frequency analyzing instruments are not available, the more stringent requirements of 85 dB maximum over-all noise level (C scale, flat response) shall be used. The specifications went on to prescribe sound meters and test-room and field-test procedures.

For the Rochester, New Hampshire 3.9 mgd Advanced WWTP, the author specified three electric-motor-driven multistage centrifugal blowers for supplying air to activated sludge aeration basins. The blowers have a rated capacity of 1930 scfm with an inlet air temperature of 100 deg F and an inlet pressure of 13.95 psia. Inlet butterfly valves perform the functions of unloading the blower in conjunction with the discharge blow-off valve during startup, and then controlling the flow by inlet throttling from 100 percent inlet flow to approximately 66 percent inlet flow. The blowers are driven by 125 hp 3600 rpm open drip-proof squirrel-cage induction motors. Inlet and discharge silencers were specified to meet specified sound levels. Those specifications were the same as those given above for the Cranston blowers, except that the 90 dBA levels were applied to each individual blower during shop testing. The specifications went on to prescribe sound meters and test-room procedures.

Noise generated in centrifugal compressors can cause resonant conditions in the downstream piping. That can cause serious compressor-system noise problems. In some cases it is possible to predict and avoid such resonance conditions by design. However, in other cases it will be necessary to use in-line silencing devices to absorb the excitation energy before it reaches the resonant pipe section [72, 73]. A related problem is air-conditioning duct noise discussed, with control methods, in Reference [74].

Rotary Positive-Displacement Blowers

Rotary positive-displacement blowers were specified by the author for the Cranston, Rhode Island 23 mgd Wastewater Treatment Plant, for which the blowers were for sludge blend tank mixing. These rotary blowers are of the two impeller, straight-lobed, positive-displacement type. Each blower delivers air over the range of 400 to 905 scfm at a pressure rise of 4.5 psi with an inlet air temperature of 68 deg F and an inlet pressure of 14.7 psia. Each blower is driven by a three-speed motor with maximum rotative speed of 3500 rpm, and with capacities of 905 and 600 scfm at the top two speeds. Discharge silencers are of the chamber type.

Another example is for the Rochester, New Hampshire 3.9 mgd Advanced WWTP, for which the author specified four such blowers for supplying air to equalization basins and waste activated sludge holding tanks (the latter for aeration and mixing). These rotary blowers are of the two impeller, straight-lobed, positive displacement type. Two of the blowers have a rated capacity of 820 scfm with turndown to 410 scfm and two have a fixed rated capacity of 250 scfm, both types with an inlet air temperature of 100 deg F and an inlet pressure of 14.3 psia. The larger blowers are driven by two-speed motors, while the smaller blowers are driven by single speed motors, all of the open drip-proof squirrel-cage induction type with maximum rotative speeds of 1800 rpm. Specified discharge pressures at the blower flange are 21.2 psia and 22.7 psia for the larger and smaller blowers respectively. Maximum specified sound levels were 88 dBA for the 820 scfm blowers and 89.5 dBA for the 250 scfm blowers. Shop noise testing was specified.

Also for Rochester, New Hampshire, the author selected an 8-inch chamber-type inlet silencer for use with an air blower of 2,462 cfm peak design inlet capacity and corresponding inlet density of 0.06107 lbm/ft³. The manufacturer's formula (Burgess-Manning Inc., Orchard Park, New York) for silencer pressure drops with dry air is as follows: $\Delta p = C(V/4005)^2\left(p/14.7)(530/T)\right)$ in which Δp = pressure drop through the silencer in inches W.C., V = air velocity through the silencer in feet per minute, Δp = pressure drop coefficient, p = absolute pressure in psia at the silencer (inlet or discharge pressure), and T is absolute temperature in deg R. The pressure drop coefficient is given as 4.2. We want to determine the corresponding value of K in a pressure drop formula of the form $KV^2/(2g)$ and the pressure drop in psi for the silencer. We commence by establishing the basis for the manufacturer's formula, and adapt the relationship for use with humid air. Using the relationship $h_L = \Delta p/\left(\rho g/g_o\right) = KV^2/(2g)$ and the perfect gas relationship $[\rho = p/\left(RT\right)$ in which p is the absolute pressure, m is the mass of the gas in volume V, T is absolute temperature, and R is an experimental gas constant which differs for each gas and for air at the temperatures of interest is 53.34 ft lbf/(lbm °R)], the following is obtained:

$$\Delta p = K\frac{\rho V^2}{2g} = K\frac{p}{R_a T}\frac{V^2}{2g} = K\frac{p}{R_a T}\frac{p_s T_s}{p_s T_s}\frac{V^2}{2g}$$

$$2gR_a = 2(32.2)(53.34)\ \frac{\text{ft}^2}{\sec^2 {}^\circ R}$$

$$\Delta p = \frac{K}{T}\frac{pV^2}{2(32.2)(53.34)}\frac{530}{530}\frac{14.7}{14.7}\left(\frac{1}{60}\right)^2(2.307)(12) = \left(\frac{V}{4013}\right)^2 K\left(\frac{p}{14.7}\right)\left(\frac{530}{T}\right)$$

in which the units are comparable to those of the manufacturer's formula. The two equations are practically identical (the differences probably are attributable to a small difference in a constant or conversion factor), and indicate that K and C are essentially identical. Thus K should be taken as 4.2, and the pressure loss can be calculated from $KV^2/(2g)$ with V being the actual velocity based on the 6-inch nominal inlet diameter of the silencer. Thus:

$$V = \frac{2462}{\left(\pi/4\right)\left(8/12\right)^2} = 7053\text{ ft/min } \div\ 60 = 118\text{ ft/sec}$$

$$\frac{V^2}{2g} = \frac{\left(118\right)^2}{2\left(32.2\right)} = 215\text{ ft}$$

$$h_L = K\frac{V^2}{2g} = 4.2(215) = 901\text{ ft of air x }\frac{0.06107}{144} = 0.382\text{ psi}$$

As can be seen from the above example, it is important to understand the basis for manufacturers' pressure drop formulae, and to be able to convert the formulae to a convenient form [the author prefers the $KV^2/(2g)$ form] or to convert results computed from the formulae to the desired dimensional units. Valves, flow meters, and gas distribution systems (e.g., air diffusers) are additional appurtenances for which such conversions are necessary.

XI. Pile Driving

Pile driving can be a significant cause of noise complaints. It can sometimes be avoided by using alternative methods. The Town of Winthrop participated in design review of the largest of the Fast-Track projects (Pump & Power Station Improvements), which was instrumental in avoiding pile driving. Foundations were placed on auger-bored concrete piles. The change enabled the reduction from 300 driven piles to 100 bored concrete piles at little extra cost. In such cases, holes can be bored to bedrock and reinforced-concrete piles poured in place.

At the author's request, specifications further called for any rock drilling to be by rotary or "down-the-hole" rotary percussive drilling methods, which avoided above-ground percussive drilling and thus resulting in no audible noise in Winthrop. Similar means of noise-averting pile construction were included in all other pertinent Fast-Track construction projects (Winthrop Terminal Upgrade, Sedimentation Rehabilitation). That included drilled cast-in-place (grout pressure injected) reinforced-concrete piles.

Deer Island pier construction was an area in which the Town's involvement resulted in design specifications intended to avert audible construction noise in Winthrop. Pier construction had three potential sources of construction noise: dredging, concrete batch plant operation, and pile driving. The author's efforts proved successful for dredging and batch-plant operation. Pile driving, however, resulted in noise complaints from the Point Shirley residents nearest Deer Island.

Following up on the experience gained from the pier construction, the author worked with MWRA to develop improved specifications for the subsequent Early Site Preparation (ESP) contracts, of which there were several on Deer Island. For those, an acoustical consultant was brought in to work with MWRA in preparing specifications and noise monitoring. That led to an improved situation. Based on the 5,200-foot distance from the pile driver to the Winthrop Town Line, the specification called for 89 dBA at 200 feet. The following were specified:

- The Contractor shall engage the services of a Noise Consultant to prepare reports indicating compliance with the noise regulations stipulated in these specifications.
- The noise consultant shall measure and record the noise at the Winthrop Town Line…using representative durations throughout the Contract and for the various types of work using equipment compatible and of sufficient sensitivity to achieve data. Locations shall be selected by the Noise Consultant and they shall meet with the concurrence of the Engineer. The Noise Consultant shall submit a report on every set of measurements that are taken, noting the acceptability criteria and analyzing the required data.
- The Contractor and Noise Consultant shall use the data obtained to immediately adjust/refine the construction procedures to assure compliance with all regulations and mitigation requirements.
- Noise levels and report(s) shall be established for the pile driving operations involved with…[the various construction activities]. The Noise Consultant shall immediately notify the Contractor and Engineer of non-compliance and assist the Contractor in developing and incorporating techniques, procedures and devices to bring the noise back to acceptable levels.

Specifications called for sheet piles to be installed by vibratory methods for MWRA's construction of the North Weymouth (Massachusetts) Interceptor project [75]. Nevertheless, complaints were received from nearby residents about noise and vibration from pile driving [76].

As a means of preventing audibility of pile-driver impact noise during pier construction, MWRA proposed to place a shroud around the impact area of the pile driver. The shroud was constructed and installed by the Contractor, whereupon the pile-driving operators' union objected to the use of the shroud, ostensibly for safety reasons (it was more related to attempts to unionize construction on the site). That led ultimately to cooperative discussions between MWRA and the author in which agreement was reached on a higher pile-driver noise limit based on the masking of pile driving noise by other construction noise. Further details are given below. It is noteworthy that shrouding has been implemented elsewhere, as indicated in Reference [77].

For subsequent Deer Island projects, the author coordinated with MWRA to develop improved specifications. For example, for the construction of a power plant on the island, specifications called for the following:

- Noise emitted by pile driving operations during the daytime hours (7:00 a.m. to 7:00 p.m.) excluding weekends and federal holidays shall not exceed 84 dBA at 200 feet.
- All noise monitoring specified…shall be performed by the Contractor's noise consultant….
- For the installation of each of the first ten (10) piles, the Noise Consultant shall measure the Lmax (maximum noise level experienced during a particular time period) at 200 feet in the direction of the Town of Winthrop using the "fast" meter response. All measurements shall be taken at a point with direct line-of-sight to the pile.
- If the noise from pile driving operations exceeds the 200 foot noise level criterion then the Contractor shall immediately modify their operation until conformance is achieved. This may include, but not be limited to, using a smaller driver, finding a quieter driver with noise mitigation such as an acoustical shroud, baffle, etc., erecting a barrier wall, or using a different type of pile.
- Repeat the [test] procedure...after making any change or modification to pile driving equipment or procedure.

- Immediately after compliance with the 200 foot limit has been successfully demonstrated, the Noise Consultant shall measure the Lmax using the "fast" response of the meter during the installation of at least five (5) piles per day. The noise shall not exceed the site MOU requirement for the current time period [refers to the MOU provisions given above under **V. Wastewater Treatment Facilities -*Winthrop, Massachusetts***]. Daily monitoring shall continue until compliance is achieved on at least two days of downwind conditions. Downwind conditions are defined as that condition when the wind is blowing from a general southeasterly direction at a speed of at least 10 m.p.h. If at any time the level exceeds the MOU limit, the Contractor shall modify their operation as described [above].
- After compliance is achieved at 200 feet and at the Winthrop Town Line, pile driving noise monitoring shall be suspended pending any future change in equipment, modification to the pile driving operation or detection of exceedance of the MOU at the Winthrop Town Line through routine CM [Construction Manager] noise monitoring. If any of these occur the procedure [given above] shall be repeated.
- Submit the following…. a. Calculations, manufacturer's noise levels data, and/or published noise level data indicating the ability of the chosen pile driver to meet the specified 200 foot noise level criterion for the type of piles to be driven. b. Results of all noise level monitoring. c. Shop drawings and calculations for any noise control if necessary.

Reference [78] notes that reducing noise from pile driving benefits not only the community but workers on the job site as well. That reference itemizes options to consider for controlling pile driver noise as follows:

- Pre-auger or pre-trench the pile holes to loosen the ground (-5 to -10 dB).
- Use a nylon or rubber pile cap cushion on top of the piles (-5 to -10 dB).
- Use a bellows system around the pile as a noise enclosure (-15 to -20 dB).
- Use temporary noise barriers mounted close to the pile driver (-5 to -10 dB).
- Use a vibratory pile driver instead of an impact pile driver (varies depending on piles and soil types).
- Use a hydraulic pile driver instead of an old diesel pile driver (-5 to -10 dB).
- Use a different system altogether such as slurry walls or a hydraulic pile pusher.
- Restrict the time of day when pile driving operations can occur.

Additional options are given by Reference [79, P. 51].

XII. Miscellaneous Noise Sources

Satellite Fire Station

Massport proposed to construct a satellite fire station in Winthrop, Massachusetts, which by a quirk of geography is actually encompassed by Boston on the side of Boston facing Winthrop across Boston Harbor. Ambient noise levels in Winthrop were characterized by measurements made over a six-month period at two locations in Winthrop. The Massport report stated the following: "Noise sources contributing to ambient L_{eq} noise levels included local traffic and aircraft taking off from Logan Airport. (L_{eq}, or Equivalent Level, is the steady-state sound level during a given period of time that has the same acoustical energy as the fluctuating noise levels during that same period, also referred to as "average sound level".) The lowest ambient L_{eq} noise level found was 55 dBA. "This value was used as a conservative (because it is low) representation of ambient L_{eq} noise levels in Winthrop." [80] It is, however, completely inappropriate to propose an ambient noise level biased by, e.g., aircraft overflights for a noncoincident noise source, rather than use the ambient level between overflights. As noted in the discussion of Noise Regulations above, the residential/conservation daytime noise standard for Winthrop is 45 dBA, well below the 55 dBA level.

Refrigeration Trucks

The author assisted a homeowner in Franklin, Massachusetts, USA and his attorney in mitigating the impacts of a large dairy operation. The problems included many "reefers" (refrigeration trucks) operating during night-time hours and loud workers outdoors near the homeowner's property. The dairy agreed to relocate the reefers further from the homeowner's property and have security better control the workers.

A similar situation occurred in Canton, Massachusetts, USA at a food service company next to a condominium complex. One of the problems was tailgates banging on the loading dock, which was ameliorated by rubber matting to reduce the noise of slamming metal. The "incessant drone" of idling reefers was reduced by the town's banning of parking from 10 p.m.to until 7 a.m. in certain areas. Residents recorded sound levels up to 85 dB. The situation was eventually ameliorated by the company's construction of a 475-foot long, 28-foot high wall inside the company's fenced enclosure. [81]

Another situation involving neighbors complaining about noise from reefers occurred in the vicinity of a business called Muffin Town in Winthrop, Massachusetts. This was reported in articles in the Winthrop Sun Transcript dated May 16, 1990; May 23, 1990; and November 19, 1992. Measurements by the Building Inspector showed noise readings above the Town's allowed decibels levels. Under the threat of a criminal complaint by East Boston Criminal Court, the reefers were relocated.

Recycling Center

The author was engaged to comment on a Draft Environmental Impact Report (DEIR) for a Recycling Center proposed in the Town of Wrentham, Massachusetts, USA. The author's comments to the Massachusetts Executive Office of Environmental Affairs focused on a noise assessment prepared by the proponent. Construction and operating noises were addressed. The DEIR was prepared by the former Secretary of Environmental Affairs for the Massachusetts Department of Environmental Protection. The DEIR, among other things, stated that noise would be controlled to be in compliance with MDEP noise regulations and that DEP noise meters would be used to confirm that. The deficiency of the MDEP noise regulations was noted along the lines discussed above under **IV. Noise Regulations - *Problematic Noise Regulations***. The author also criticized the fact that no total noise estimates were made nor did DEP possess any noise meters. Individual equipment noise estimates were also questionable. For example, 7-cy front end loaders on the tipping floor and compost area were assumed to have noise levels of 78 dBA and a 10-cy front end loader in the curing area was assumed to have a noise level of 80 dBA. However, front end loader in that size range typically have maximum sound pressure levels of 86-88 dBA at 50 feet (per Table B.1 of [60]). The author noted numerous other deficiencies in the DEIR. Based on the author's comments on the above and other matters, the then-current Secretary of Environmental Affairs denied the project as proposed.

Tailgate Banging

Tailgate banging can be a nuisance and can be the cause of complaints. For example, in February 2001 the author was made aware of related citizen complaints due to trucks coming along the roadway to the Granite Rail Quarry for which the author represented the City of Quincy, Massachusetts, USA. The quarry was being filled primarily with deep soil mix from the Boston Central Artery Tunnel project. That quarry has since become part of an area of park and historical attractions. Such banging can be controlled by installing or repairing tailgate rubber stripping or rubber stops. Regulations intended to prevent tailgate banging are promulgated by various jurisdictions, such as the Massachusetts Department of Transportation Type I and Type II Noise Abatement Policies at Section 13.0 Construction Noise, and Cave Springs, Arkansas Code of Ordinances §114.05 Control of Dump Truck Tailgate Banging and Loader Banging.

Wetlands Protection

To protect the Commonwealth of Massachusetts, USA wetland resources, the Massachusetts Wetlands Protection Act requires that a permit be obtained for activities involving the removal, dredging, filling, or altering of wetlands. To obtain the permit, called an Order of Conditions, a proponent must submit a descriptive Notice of Intent (NOI) application to the municipal Conservation Commission and the Massachusetts Department of Environmental Protection (MDEP). The former has first- line responsibility for assuring that the proposed work meets the performance standards described in the State Wetlands Protection Act Regulations, 310CMR10.00 (CMR being an initialism for Code of Massachusetts Regulations).The Conservation Commission issues an Order of Conditions stipulating requirements with which the work must comply, and is further responsible for inspections to assure compliance. Once issued by the Conservation Commission their Order is binding unless appealed to the MDEP, which can uphold or modify the Order. The law provides for actions that may be taken by either of those agencies for dealing with violations of the Order. Projects in which the author has used Orders of Conditions to include noise-control provisions are discussed below; none of those Orders has been appealed.

Beach Nourishment

For a project involving beach nourishment in Winthrop, Massachusetts, the author's suggested wording in the Order of Conditions included the following: "In view of the fact that certain construction work will be carried out 24 hours per day, seven days per week, in close proximity to Winthrop residents, and with major potential to have adverse impacts, the Winthrop Conservation Commission considers it important that noise…be adequately mitigated. The plans for such mitigation, as identified below, shall be submitted at least one month prior to commencement of construction. Those plans shall be submitted to the Winthrop Conservation Commission (WCC) for review by the WCC and others in Winthrop and approval by the WCC. The WCC designates the proposed project as major construction under Winthrop's Noise Control Regulations (discussed above) at §242-5.G. A work plan shall be submitted detailing the noise control and mitigation measures to be taken. The plan shall include but not necessarily be limited to measures stated in the Final Environmental Impact Report, irrespective of context (upland vs. beach work)…with additional appropriate details. The plan shall also identify construction that can reasonably be done at times other than nighttime, weekends, and holidays as defined in §242-5. For example, groin demolition, cap removal, and construction should take place at times other than nighttime, weekends, and holidays.

Beach Improvements

For a project entailing improvements to Short Beach in Winthrop, the author's suggested wording in the Order of Conditions included the following: "Except as otherwise approved by the Winthrop Conservation Commission in accordance with Winthrop's Noise Control Regulations (discussed above) at §8.20.060, construction shall be limited to daytime hours (defined as the period between the hours of seven a.m. and six p.m.) and shall further not be allowed on weekends and federal holidays."

Windmills

Wind power is a very important component of a clean-energy future that greatly reduces the use of fossil fuels and attendant global warming and air pollution. Sweden has been a global leader in the use of wind power, and doing so in an unobtrusive way by placing single units in large fields widely dispersed (the author observed many of these while traveling in Sweden). Propagation modeling parameters for wind power projects are discussed in Reference [82].In the United States, wind power has been controversial due to flickering shadows in residential areas, visual impacts of large wind power farms, bird kills, bat kills, and noise. It is important to establish baseline environmental sound levels for wind turbine projects [83]. The following are examples of poor outcomes associated with windmills.

One unfortunate situation was in the Town of Falmouth, Massachusetts, USA [84] [85], where two wind turbines, poorly sited, became the subject of complaints and lawsuits filed by neighbors affected by noise and associated health issues. The Town ultimately paid more than $40,000 to have the windmills demolished. And the Massachusetts Clean Water Trust, that loaned the Town $4,865,000 to build the windmills, agreed to accept only $975,000 to resolve the loan.

Another situation was in the Town of Hull, Massachusetts [86]. One of the wind turbines had deteriorated to the point of not being operable. The other was so poorly designed to withstand the elements that it was out of commission. On February 18, 2024, one of the wind turbines was taken down. The situation remains unresolved for the other one.

In the fall of 1993, the Massachusetts Division of Energy Resources proposed to construct a 100-foot tall wind-monitoring tower on Deer Island to obtain wind data for about one year and subsequently install two or three 250-350 KW windmills on a man-made hill in close proximity to the Winthrop town line. The windmills would be more of a demonstration project, as that capacity represents only a few percent of the Deer Island demand. The author put an end to that proposal by noting that the Deer Island Water Pollution Control Facility had fully utilized the noise allocation (36 dBA transmitted to the Town line) for the island.The project was resurrected in 2009 with the installation at the end of the island most distant from Winthrop of two windmills. Then, in May 2023, one of the windmill started spinning out of control and a piece of blade came flying off the 100-foot tower. The second turbine was shut down as a precaution, and remains out of service [87] [88] .

In Scituate, Massachusetts, a 400-foot-tall 1.5 MW wind turbine is located at the Town's wastewater treatment plant. Neighborhood complaints have included noise, shadow flicker (the turbine is just 650 feet from the nearest home), sleep disturbance, health impacts, vibration, and inadequacy of antiquated Massachusetts' testing methods and standards [89] [90] [91] [92] [93] [94]. A seasonal hiatus was proposed [57] which was said to cost the town about $96,000 according to data from Scituate Wind, the private company that owns and runs the turbine on town property under a contract with the town.

Other Massachusetts communities with wind turbine complaints include Kingston, Hanover, Charleston, and Fairhaven [89]. "Kingston, Bourne, Plymouth, and Falmouth have declared their wind turbines a public health nuisance…Barnstable and Plymouth Superior Court judges have upheld these nuisance declarations and supported those towns' ability to legally shut down their operations without financial penalty." [93]. All of these problems, as are others mentioned above are in heavily-populated communities.

Back-Up Alarms

Construction vehicle back-up alarms have been the cause of complaints at numerous construction sites, e.g. at the Quarry Hills site in Milton, Massachusetts, USA [95]. At that site the Occupational Safety & Health Administration (OSHA) denied a waiver request to eliminate the beeping. If the beeping is silenced, OSHA requires that an attendant be on duty instead, but that can require three people in cases such as when there is a fill-hauling truck, bulldozer, and backhoe packing the fill on a pile. Restricting nighttime work is one option, but may not be feasible in some cases. The disturbance caused by backup alarms can be reduced by the use of audible self-adjusting backup alarms.[96] They can be set to activate at 5 decibels above background noise.

Concrete Manufacturing Plant

A concrete manufacturing plant in Holbrook, Massachusetts, USA was the subject of noise complaints. Once again, the plant operator rationalized that the plant should not be a nuisance because it met the Massachusetts 10 dBA above background requirements and there were other nearby noises [97] .

Superfund Cleanup Site

Another issue in Holbrook, Massachusetts was noise associated with a Superfund Cleanup Site [98] which added insult to injury (literally, as neighbors in the vicinity of the site had an excess of cancers and related deaths).

Junkyard Noise

Smashing glass, loud clanking, loud voices, and swearing were the cause of complaints by residents of Quincy, Massachusetts, USA. Culminating 11 years of complaints (too long!), when license board hearings failed to resolve the issue the Assistant City Solicitor obtained a court order in Norfolk County Superior Court. The junkyard was directed to do all salvage work indoors, prohibits trucks other than those owned by the junkyard from dropping junk off at the yard, and requires keeping all trunks and junk inside a building. [99]

Leaf Blowers

Noisy leaf blowers are often a serious noise nuisance, e.g. reported in Reference [101]. More than 100 cities in seven U.S. states have imposed complete or partial bans on leaf blowers [101]. Gas-powered leaf blowers are the noisiest at 80 to 90 dB. Electric models are quieter with a decibel range between 65 and 70. A few new models of electric leaf blowers (e.g., one by Ryobi) come in at 59 decibels.

Highway Noise Barriers and Acoustical Buffer Zones

The subjects of highway and railroad noise barriers and acoustical buffer zones for highways are addressed in a number of good references ([102], [103], [104], [105], [106], [107], [108], [109], [110], [111], [112], [113]).

Automobile Antennas

Automobile antennas have been a source of a whistling sound caused by a wake of alternating vortices. Wind flowing over an antenna of uniform cross section along its length creates vortices that shed in symphony and generate a piercing whistle. Those sounds have been reduced by production of conical antennas, which distributes the frequencies from the top to the bottom of the antenna, resulting in a collage of frequencies, or a hum, that is more pleasant to the ear. Some antennas have grooves that to distribute the frequency even more.

Outdoor Kart Racing Complex

A large outdoor kart racing complex in East Bridgewater, Massachusetts, USA was fined $2,995 by the MDEP in November 2006 for noise exceeding the background noise level by more than 10 dBA. The MDEP investigation was prompted by a resident's complaint. Subsequently, as part of a special permit issued by the East Bridgewater Planning Board, the owner installed an 800-foot-long sound barrier at a cost of about $600,000 to try to curb the noise. [114]

Noise in the Sea

A paper entitled "Noise in the Sea and Its Impacts on Marine Organisms" [115] provides a comprehensive discussion of the impacts of anthropogenic sounds in marine waters. Boating and shipping noise; seismic testing/exploration; seismic air guns; sonar; oil drilling; mining; pile driving; tidal turbines; and underwater blasting were found to cause a range of adverse effects on marine life. These variously include startle; forced emigration; reduction in auditory sensitivity of certain fish; short-term reduction of the hearing range of harbor porpoise and bottlenose dolphin; severe damage to the ears of the pink snapper; masking the ability of the Lusitanian toadfish to perceive sounds; massive acoustic trauma to cephalopods including octopi; cochlear damage; reduced nest digging and defensive behavior of cichlid fish; reduced protection against predators by Caribbean hermit crabs and the European green shore crab; behavioral disturbance of minke whales as far as 40 km from a pile-driving location; mass strandings and severe physical damage to three species of beaked whales, giant squid, Kemp's ridley sea turtles, and bottlenose dolphins attributed to anthropogenic noise; decreased catch rates of cod, pollack and haddock; body malformations of larval scallop; reduction in reproduction and growth rates of White Sea brown shrimp; increased susceptibility of hybrid striped bass to barotrauma injuries (i.e. body injury due to change in water pressure); significantly smaller body weight of lined seahorses; and depression of the immune system of white whales. Organisms with no acoustic receiving structure can also be effected due to impulses on their body surface, such as the New Zealand scallop.

Acoustical Weapon

An interesting application of acoustics for defensive purposes is exemplified by the use of a sonic weapon by the crew of the cruise ship *Seabourn Spirit* to ward off an attack by a gang of pirates in two small boats off the coast of Somalia. The crew used a long-range acoustical device (LRAD) capable of producing 151 dB at 1 meter and 105 dB at 300 meters, compared to smoke alarms which produce 80 to 90 dB at 1 meter. [116]

An interesting application in the natural world is the transparent micro glassfish (*Danionella cerebrum*) [117]. One of the smallest known vertebrates, it has an adult body length of approximately 12 mm (about one-half inch), and the smallest known vertebrate brain. The glassfish employs an indirect sound production mechanism where a drumming cartilage snaps out and strikes the swim bladder upon muscle contraction. The adult males produce clicks at repetition rates of 60 and 120 Hz by repeated unilateral or by alternating bilateral contractions. The high amplitude sounds exceed 140 dB (re 1 uPa) at a distance of one body length, comparable to a jet engine during takeoff in 100 meters distance. The species is native to the shallow and turbid waters of Myanmar. The competition between males in this visually-restrictive environment is believed to have contributed to this special mechanism for acoustic communication. [118]

Another natural world application is the more-studied, multi-genera snapping shrimp aka pistol shrimp, said to be the "most persistent and most widespread biological noise" [119]. Under certain conditions, they can completely dominate the ambient noise in the sea [120]. They live in a variety of tropical and subtropical shallow water ocean locations, from coral reefs to temperate kelp forest to sponge-dominated and rocky-bottom habitats. They range in length from a couple of centimeters in length [approximately ¾ inch] to about 5 centimeters (2 inches). Their outsize snapping claw, significantly larger than their other claw, can grow to be half the size of their body. The claw cocks open and snaps shut at high speed. This generates tiny bubbles that implode, sending a shock wave which stuns and even kills small crabs, worms, and other prey; communicates with others such as for mate attraction; repels combative snapping shrimp; and deters predators [121, 122, 123, 124]. At 183-210 decibels, this makes them some of the loudest sound producers in the ocean. Their sound plays an important role in directing marine life to suitable habitats; their return to suitable habitats can alert other organisms to the suitability of the habitat and thus rebuild ecological communities. [125] Snapping shrimp sounds contribute most to coastal biological noise, and may be heard up to 1 mile away. Hydrophone measurement have revealed pulse-like signals of 500-nanosecond duration, with frequencies beyond 200 kHz, and showing enormous sound pressure levels of up to 200 dB re/ 1 μPa (peak to peak) at 1-meter distance. Ultra-high speed video recordings and simultaneous hydrophone measurements reveal that claw closure results in a water jet, the high velocity of which (25 m/s) leads to the formation of a cavitation bubble, which emits the extremely loud sound upon its collapse. [126] More precisely, cavitation entails the formation of vapor cavities in a liquid flow when the pressure falls below the vapor pressure of the liquid. Scientists have also found that light is produced when the bubble pops due to the high temperatures and pressure inside the bubble. [119]. The combined sound of large aggregations of snapping shrimp is so prevalent in certain areas of the world that it interferes with underwater communications and research [124]. One interesting characteristic of several species is that if the large claw is removed, a smaller one replaces it but the opposite, previously-small one, becomes a large crusher claw at the next molt [124].

Active Sound Control

Active sound control is a technique that involves measuring unwanted sound (aka noise) and introducing sound waves opposite to that sound in an attempt to cancel the unwanted sound. It has yet to materialize into practical applications at a significant scale for non-industrial applications, with social acceptance and cost being key issues [44], [127], [128], [129]. Industrial applications have been reported [129], but those industries have not remained in operation for long. One successful exception is active control of a 369-kW natural-gas-fired generator for a municipal water-lift (pump) station in a Long Island, New York community [130].

XIII. Property Values

Point Shirley and Cottage Hill Impacts

The author was tasked with assessing the effects of construction and operation of the Deer Island Wastewater Treatment Plant (discussed above) on the adjacent Point Shirley and Cottage Hill neighborhoods in the Town of Winthrop, Massachusetts, and to propose mitigation measures. Factored in was the traffic on the narrow roadway leading through Winthrop to Deer Island and the impact of being in the flight path of nearby Logan International Airport (as discussed above under **Sound Insulation**).

Part of the author's efforts to assess the impacts was to present research that clearly demonstrated the impact on property values. Useful related research was obtained from references [26], [61], [131], and [132], which clearly demonstrate that property values are diminished by proximity to airports and highways. References [131] and [132] found property value decreases of 0.4 to 1.1% per decibel increase. The author used that information and property values in the impacted area to derive economic impacts. Mitigation measures negotiated and overseen by the author are discussed above under **VI. Sound Insulation** and are not limited to that topic..

A more recent noise impact is associated with the game of pickleball. Many pickleball courts are outdoors and near people's homes. Although beneficial to the players, noise concerns have caused residents to complain to their elected officials, and given rise to petitions and legal actions aimed at limiting the sport and preventing the construction of new courts [133, 134]. The reduction in real estate prices for residential properties have been quantified as being from 5% to 20% depending on proximity to the courts [135].

XIV. Conclusions

Focusing on outdoor noise, this paper first discusses historical reports of outdoor noises and more recent related observations. Sound propagation, hearing, and health effects are addressed. Additional topics discussed are noise regulations, noise impacts of and mitigation for wastewater treatment facilities, sound insulation, and noise barriers. Noise levels and physical damage of blasting and control methods are addressed Cavitation is addressed with the focus on noise. There is further discussion of silencers for centrifugal dynamic blowers and rotary positive-displacement blowers. Pile driving can be a significant cause of complaints; alternatives and mitigation are addressed. Numerous miscellaneous noise sources are discussed. Effects of construction and operation of facilities on property values are discussed. along with compensatory mitigation.

Acknowledgment

The author acknowledges Wayne E. Bradley, formerly of Stone & Webster. Engineering Corp., from whom the author learned much about noise mitigation in the course of working with him on various engineering projects.

References

[1] Graber, S. D. (2012a). "Perspective on the Tidal Bore: Background and Initiation." Proceedings of FEDSM2012: 2012 ASME Fluids Engineering Summer Meeting, July 8-12, 2012, Rio Grande, Puerto Rico.
[2] Postel, S., Richter, B. (2003). Rivers for Life: Managing Water for People and Nature, Island Press.
[3] Wood, J., (1841). "Personal Narrative of a Journey to the Source of the River Oxus by the Route of the Indus, Kabul, and Badakhshan Performed Under the Sanction of the Supreme Government of India in the Years 1836, 1837, and 1838." John Murray, London.
[4] Chanson, H. (2016). "Atmospheric noise of a breaking tidal bore." Journal Acoustical Society of America, 139(1), Pp. 12-20.
[5] Graber, S. D. (2023a). "Thermodynamic Concepts in Civil Engineering,, IOSR Journal of Mechanical and Civil Engineering, 20(5), Ser. 2, Pp. 8-23.
[6] Cropper, W. H. (2001).. Great Physicist*s*, Oxford University Press, New York, Chapter 5.
[7] Al-Musawi, T. T. A. (2012). Acoustical Design Of Water Features And Their Use For Road Traffic Noise Masking, Submitted for the degree of Doctor of Philosophy, Heriot-Watt University School of the Built Environment, Edinburgh, Scotland, October 2012.
[8] Lilly, J. G.(2007). "Waterfall Noise." 154th Meeting, Acoustical Society of America, New Orleans, Louisiana, November 28, 2007.
[9] Perley, S. (2001). Historic Storms of New England, Chapter II: The Earthquake of 1638, Commonwealth Editions, Beverly, Massachusetts (Reprint of 1891 edition). Also http://earthquake.usgs.gov/earthquakes/states/events/1638_06_11_hs.php, accessed 7/16/2013.
[10] Lewis, A., Robinson, J. (1865). History of Lynn, Vol. 1, Boston Public Library: 974.462 L18 L3.1 V1.
[11] Greenlaw, L. (2005). All Fishermen are Liars: True Tales from the Dry Dock Bar, Hachette Books, New York City.
[12] Parkin, P. H., & Scholes, W. E. (1965.) "The Horizontal Propagation of Sound From a Jet Engine Close to the Ground,." Sound and Vibration, 2(4), Pp. 353-374
[13] Maekawa, Z. (1968). "Noise reduction by screens." Applied Acoustics, 1(3), Pp. 157-173.
[14] Piercy, J. E., & Embleton, T. F. W. (1979). "Sound Propagation in the Open Air." Chapter 3 in Handbook of Noise Control, C.M. Harris (ed.), McGraw Hill, 2nd edition.
[15] Kurze, U. J., & Beranek, L.L. (1988) "Sound Propagation Outdoors." Chapter 7 in Noise and Vibration Control, LL. Beranek (ed.), Institute of Noise Control Engineering, Washington, D.C.
[16] Acoustical Society of America (1978). Method for the Calculation of the Absorption of Sound by the Atmosphere, ANSI S1.26-1978 (ASA 23-1978), New York, New York.
[17] Anderson, G. S., & Kurze, U. J. (1992) "Outdoor Sound Propagation." Chapter 5 in Noise and Vibration Control Engineering, LL.. Beranek and I.L. Vér (eds.), John Wiley & Sons, New York.
[18] Beranek, L.L. (1966). "Noise Scientific American, 215(8), Pp. 66-76.
[19] Cohen, A.(1965). "Physiological and Psychological Effects of Noise on Man." Journal Boston Society of Civil Engineers, 52(1), Pp. 70-95.
[20] Berdik, C. (2018). "SOUNDING THE ALARM!." The Boston Globe, May 20, 2018.
[21] Bolt, Beranek, & Newman Inc. (1971). NOISE FROM CONSTRUCTION EQUIPMENT AND OPERATIONS, BUILDING EQUIPMENT, AND HOME APPLIANCES." Prepared for the U.S. Environmental Agency Office of Noise Abatement and Control, Washington, D.C.
[22] Silberner, J. (2024). "A Healthy Dose of Quiet." Scientific American, 330(5), Pp. 58-65.

[23] Gales, R. S.. (1979). "Hearing Characteristics." Chapter 8 in Handbook of Noise Control, C.M. Harris (ed.), McGraw Hill, 2nd edition, P. 8-6.
[24] Peterson, A. P. G.. (1980). Handbook of Noise Measurement, GenRad, Inc., Concord, Massachusetts, Ninth edition, Pp. 58, 69-70.
[25] Anon. (2024). Title 24-Housing and Urban Development…Subpart B Noise Abatement and Control §51.103 Criteria and standards (c) Exterior Standards, amended 4/08/2024.
[26] Nelson, J. P.(1979). "Airport Noise, Location, Rent, and the Market for Residential Amenities." Journal of Environmental Economics and Management, 320-331.
[27] Miller, J. F. (1979).. "HUD Policy: Noise Assessment of Building Sites." Handbook of Noise Control, C.M. Harris (ed.), McGraw Hill, 2nd edition., Chapter 44.
[28] Anon. (1991). "Fix noisy sludge fans." The Patriot Ledger, Quincy, Massachusetts, November 22, 1991.
[29] Miller, M.L. (1985). "Noise Control" Chapter 12 in Environmental Law Handbook, Government Institutes, Inc., Eighth Edition.
[30] Anon. (1990). "EPA branch silent but man still hears noise complaints." The Boston Globe, March 20, 1990.
[31] Mercer, M. (2002. "The government has grown silent about noise." The Patriot Ledger, Quincy, Massachusetts, March 26, 1990.
[32] Anon. (1999). "NOISE: A RISING RACKET THREATENS OUT HEARING AN OUR QUALITY OF LIFE. WHY ISN'T THAT MESSAGE BEING HEARD?" Consumer Reports, September 1999, Pp. 19-22..
[33] Long, P., & Lebowitz, L. (2005). "NEW LAW LOWERS THE BOOM ON MUSIC." Miami Herald, May 21, 2005.
[34] Anon. (2000). "Rutland officials consider law regulating stereo noise." The Patriot Ledger, Quincy, Massachusetts, August 12-13, 2000.
[35] Center for Disease Control (CDC) (2024) "Occupational Noise Exposure." https://www.osha.gov//noise, accessed March 24, 2024.
[36] Dolin, E. J.(2004). "Political Waters: The Long, Dirty, Contentious, Incredibly Expensive but Eventually Triumphant History of Boston Harbor-A Unique Environmental Success Story." University of Massachusetts Press, Amherst, MA
[37] Bradley, W. E., Maxon, C. M., Davies, G E., Lager, J. A. (1991). "Implementation of a Noise Control Program for the Boston Harbor Waste Water Treatment Facility." National Conference of Noise Control Engineering, Tarrytown, New York, July 14-16, 1991.
[38] Davies, G. E., Lager, J. A., Bradley, W. E. (1991). "Noise Control Program for the Boston Harbor Project', Proceedings of the 1991 Environmental Engineering Specialty Conference, Reno, Nevada, July 10-12, 1991, Pp.. 580-585.
[39] Davies, G. E., Lager, J. A., Berens, R. S., O'Brien, D. K.(1993). "Controlling Operating Noise for Boston's Landmark Plant." Joint Canadian Society of Civil Engineers-American Society of Civil Engineers National Conference on Environmental Engineering, July1993.
[40] Town of Winthrop, (1988). Memorandum of Understanding Between the Town of Winthrop and the Massachusetts Water Resources Authority, Concerning Certain Effects of the Construction and Operation of Secondary Wastewater Treatment Plant Facilities at Deer Island, MWRA.
[41] Anon. "deer island [rev].01 – WalkBoston." https://walkboston.org/sites/default/files/WalkBostonMapDeerIsland.pdf, accessed May 1, 2024
[42] Cousens, Cl, Weare, R., Mosher, B., & Walsh, M..(1965). "From disposal to beneficial use—10 years of sustainable biosolids management at the Greater Lawrence Sanitary District." NEWEA Journal, Summer 2014, Pp. 30-35.
[43] Taylor, M. & Ross, C. (2002) "Pipeline under pressure." The Patriot Ledger, Quincy, Massachusetts, May 9, 2002.
[44] Wang, S., Li, H. Zhang, P., Too, J., Zou, H., & Qiu, X. (2023). "An experimental study on the upper limit frequency of global active noise control in car cabins" Mechanical Systems and Signal Processing , 201(10), Pp. 1-6.
[45] Schultz, T. J. (1978). "Synthesis of social surveys on noise annoyance." Journal Acoustical Society of America, 64(2), Pp. 377-405.
[46] Peterson, A. P. G. (1980). Handbook of Noise Measurement, Ninth Edition, GenRad, Inc., Concord, Massachusetts, §4.22.
[47 Toffler, A. (2022). "Noise insulation to come to Winthrop." Winthrop Transcript, September 15, 2022.
[48] American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. (ASHRAE) (1987). 1987 ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Systems and Applications, ASHRAE, 1791 Tullie Circle, N.E., Atlanta, Georgia.
[49] Carpenter, J. H., (1958). "Air Conditioning." Mechanical Engineers' Handbook, T. Baumeister (ed.), McGraw-Hill Book Company, New York, Pp. 12-118 to 12-131.
[50] Benson, T. (2000). "Scituate wary of MBTA's money offer buying happiness." The Patriot Ledger, Quincy, Massachusetts, July 11, 2000.
[51] Kurze, U. J. & Schreiber, L. (1986). "Shielding of Shooting Noise by Earth Berms and Walls." Proceedings of Inter-Noise 86, Cambridge, Massachusetts, Pp. 485-488
[52] Pierce, A. D.(1974). "Diffraction of sound around corners and over wide barriers." Journal Acoustical Society of America, 55(5), Pp. 941-955.
[53] Kurze, U. J. (1973). "Noise reduction by barriers." Journal Acoustical Society of America., 55(3), Pp. 504-518.
[54] Gill, H. S. (1980). "Effects of Barriers on Propagation of Construction Noise." NTIS PB81-166829, Southampton University, England, December 1980, Pp. 111-112.
[55] Sain, C. H. (1979). "Vibration Control in Blasting." Standard Handbook for Civil Engineers, Frederick S. Meritt (ed.), McGraw Hill, Third Edition, §13-18.
[56] Laskey, F. A. (2002). "Update on Framingham Extension Relief Sewer Corrosion and Odor Control Program." Massachusetts Water Resources Authority.
[57] Eschbacher, K. (2002). "Blasting at projects annoys neighbors." The Patriot Ledger, December 21-22, 2002.
[58] Guldberg, P. H. (2000). "Highpoint Residential Project, Quincy" May 31, 2000
[59] U.S. Department of Housing and Urban Development (2022).Environmental Assessment Determinations and Compliance Findings for HUD-assisted Projects 24 CFR Part 58, Washington, DC, October 1, 20222, P. 13.
[60]. Barnes, J. D., Miller, L.N., & Wood, E. W. (1977). Power Plant Construction Noise Guide, Bolt, Beranek, & Newman Inc., Empire State Electric Energy Research Corporation.
[61] Mieszkowski, P., Saper, A. M. 1978. "An Estimate of the Effects of Airport Noise on Property Values." Journal of Urban Economics, 5, Pp. 425-440.
[62] Adams, S. (2000). "The shakes: Residents say project hurting their homes." The Patriot Ledger, Quincy, Massachusetts, September 2-3, 2000.
[63] Van Sack, J. (2004b). "Power plant-neighbors still unhappy." The Patriot Ledger, Quincy, Massachusetts, November 13-14, 2004.
[64] Ross, C.. (2002). "State grills Sithe about noise violations." The Patriot t Ledger, Quincy, Massachusetts, October 3, 2002.
[65] White, J. (2003). "State hearing expected on power plant noise." The Patriot Ledger, Quincy, Massachusetts, April 17, 2003
[66] Ross, C. (2003). "Power plan t neighbors want compensation." The Patriot Ledger, Quincy, Massachusetts, February 1-2, 2003.
[67] White, J., & Fontecchio, M. (2003). "Madden stops work on Weymouth plant." The Patriot Ledger, Quincy, Massachusetts, April 8,

2003.
[68] White, J. (2003). "Agreement on power plant reached." The Patriot Ledger, Quincy, Massachusetts, August 31, 2004.
[69] Van Sack, J. (2004a). "Power plant-related noise subsiding." The Patriot Ledger, Quincy, Massachusetts, August 31, 2004.
[70] Ball, J.W., & Tullis, J.P. (1973). "Cavitation in Butterfly Valves." Journal of the Hydraulics Division, American Society of Civil Engineers, 99(9), Pp. 1303-1318 [with errata 100(4), 620].
[71] Baumann, H.D. (2016). "How to Prevent Cavitation in Butterfly Control Valves." International Society of Automation, November/December 2016, Pp. 1-13.
[72] Kurkjian, G.A. (1978). "Proper Butterfly Valve Application Avoids Costly Repairs." Water & Sewage Works, Scranton Gillette Pub. Co., 125(6), Pp. 84-89.
[73] Seebold, J. G. (1972). "Resonance in Centrifugal Compressor Piping." *1972 ASME Petroleum Mechanical Engineering and Pressure Vessels & Piping Conference*, New Orleans, Louisiana, 72-Pet-3.
[74] Lowery, R. L. (1972). "The Common Sense Approach to Noise Control." *1972 ASME Petroleum Mechanical Engineering and Pressure Vessels & Piping Conference*, New Orleans, Louisiana, 72-Pet-64.
[75] Massachusetts Water Resources Authority (1999). "Braintree-Weymouth Relief Facilities Project Working Group Meeting." January 7, 1999, P. 13.
[76] Laskey, F.A. (2001). "Braintree-Weymouth Relief Facilities Update." Massachusetts Water Resources Authority.
[77] Kessler, F., & Schomer, P .D. (1981). NOISE: CONTROL: PILE DRIVER DEMONSTRATION PROJECT, WATERLOO, IOWA, , Construction Engineering and Research Laboratory, Champaign, Illinois.
[78] Burgé, P. L. , & Thalheimer, E. (2012). "Five Myths of Construction Noise." Sound and Vibration, 46(12), Pp. 15-17.
[79] Schomer, P. D., & Homans, B. (1975). CONSTRUCTION NOISE: SPECIFICATION, CONTROL, MEASUREMENT, AND MITIGATION, Construction Engineering and Research Laboratory, Champaign, Illinois.
[80] Massachusetts Port Authority (1992). "Air Rescue & Fire Fighting Satellite Facility." Environmental Notification Form , December 1992.
[81] Smith, S. M. (2002). "Residents welcome the sound separation." The Boston Globe, April 28, 2002.
[82] Kaliski, K., & Duncan, E. (1998). "Propagation Modeling Parameters for Wind Power Projects." Sound and Vibration, 42(12), Pp.12-13.
[83] Hessler, F. H., & Hessler, D. M. (2006). "Baseline Environmental Sound Levels for Wind Turbine Projects." Sound and Vibration, 40(11), Pp. 10-15.
[84] Anon. (2013). "Judge orders limited use of Falmouth wind turbines." The Patriot Ledger, Quincy, Massachusetts, November 23-24, 2013.
[85] Jung, A. (2022). "After years of uncertainty, Falmouth wind turbines to be demolished." Cape Cod Times, June 6, 2022.
[86] Meyer, C. B. (2022). "Wind turbines offline as light plant assess damage; Pemberton unit is beyond repair." Hull Times, November 3 ,2022.
[87] Rosenfield, M., Becker, K. M., & Rojo, C. (2023). "Part of Boston's Deer Island Closed After Piece of Wind Turbine Blade Falls Off." Wind Watch, May 30, 2023.
[88] Lima, J., & Pappas, L.(2023) "Emergency crews halt damaged wind turbine spinning out of control on Deer Island." Boston 25 News, May 0, 2023.
[89] Ronan, P. (2013). "Shifting Direction: Controversies take wind out of clean-energy turbine initiative." The Patriot Ledger, Quincy, Massachusetts, March 23, 2013.
[90] Ronan, P. (2013). "No accord on terms of turbine study." The Patriot Ledger, Quincy, Massachusetts, January 8, 2013.
[91] Ronan, P. (2013). "Town won't combine turbine tests ." The Patriot Ledger, Quincy, Massachusetts, March 30-31, 2013.
[92] Cowperthwaite, W. (2021). "Scituate turbine to stop spinning at night for six months." The Patriot Ledger, Quincy, Massachusetts, March 2, 2021.
[93] Thomson, R. (2022). "The future of the Scituate Wind turbine could be decided at Town Meeting,: Wicked Local, Needham, Massachusetts, April 6, 2022,
[94] Anon. (2022). Classified ad placed by neighbors of Scituate's Industrial Wind Turbine, WICKEDLOCAL.com, February 3, 2022.
[95] Moy, K. W. (1999). "Selectmen get earful about beeping trucks." The Patriot Ledger, Quincy, Massachusetts, June 19, 1999.
[96] Morgan, H. (2007). "Back-Up Safety Alarms Minimize Environmental Noise Exposure and Focus Warning Signals." Sound and Vibration – S&V Observer, Pp. 6-7.
[97] Kim, E. (2006). "Consultants say cement plant within allowable noise levels." The Patriot Ledger, Quincy, Massachusetts, September 7, 2006.
[98] Lilly, J. G. (1998). "Noise Control at an EPA Superfund Cleanup Site ." Sound and Vibration, 32(12), Pp. 14-19.
[99] McEarchern, R. (2000). "Junkyard ordered to quiet operation,." The Patriot Ledger, Quincy, Massachusetts, November 15, 2000.
[100] Donovan, M. (2000). "Sound of leaf blowing roars through autumn." The Patriot Ledger, Quincy, Massachusetts, November 25-26, 2000.
[101] Anon. (2024) "Why Leaf Blower Bans Are On the Rise." LeafScore, Pp. 1-6.
[102] Zulfacar, A., & Clark, C. S. (1974). "Highway Noise and Acoustical Buffer Zones." Transportation Engineering Journal, American Society of Civil Engineers, 100(2), Pp. 389-401.
[103] Anon. (2000). "Purdue Researchers Study Road Noise." Civil Engineering, 70(4), P. 32.
[104] Probst, W., & Huber, B. (2000). "Calculation and Assessment of Traffic Noise Exposure." Sound and Vibration, 34(7), Pp. 16-20.
[105] DeGasper, J. (2001). "Saving Ears or Fuel." Mechanical Engineering, 13(9), Pp.64-67.
[106] Gharabegian, A., & Tuttle, E. (2002). "Diamond Grinding for Roadway Noise Control." Sound and Vibration, 36(12), Pp. 26-29.
[107] Sharke, P. (2003). "Treading lightly: paved ribbons of speed make for noisy neighbors" Mechanical Engineering, 125(4), Pp. 40-42.
[108] Fortner, B. (2003). "Transparent Sound Wall Added to Woodrow Wilson Bridge." Civil Engineering News, 73(7), P. 29.
[109] Binns, J. (2004). Irregular Surface Increases Sound Absorption in Noise Barrier, Civil Engineering News, 74(3), Pp. 18-19.
[110] Cohn L. F., & Bowlby, W. (1984). "Minimizing Highway Noise Barrier Intrusion." Journal of Environmental Engineering, American Society of Civil Engineers, 110(3), Pp. 534-549.
[111] Matarazzo, B. (2000). "Silence is golden." The Patriot Ledger, Quincy, Massachusetts, July 7, 2000.
[112] Daniel, M. (2004). "Dimming traffic's roar." The Boston Globe, October 3, 2004.
[113] Simpson, M. A. (1976). Noise Barrier Design Handbook, Federal Highway Administration, DOT-FH-8287, February 1976.
[114] Murphy, M.. (2006). "Sound bite: State issues noise fine to F1 Outdoors kart complex." The Patriot Ledger, Quincy, Massachusetts, December 1, 2006.
[115] Peng, C., , Zhao, X., & Liu, G..(2015). "Noise in the Sea and Its Impacts on Marine Organisms." International Journal of Environmental Research and Public Health, " 12(10), Pp. 1-23.

[116] Anon. (2005). "Acoustical Weapons." Sound and Vibration, 30(11), P. 2.
[117] Groneberg, A. H., Dressler, L.E., Kadobiansky, M., Müller, J., & Judkewitz, B. (2024). "Development of sound production in *Danionella cerebrum*." https://doi.org/10.1101/2024.03.25.586601 accessed April 26, 2024.
[118] Cook, V. A. N. O., Groneberg, A. H., Hoffman, M., & Kadobianskyi, M. (2024). "Ultrafast sound production mechanism in one of the smallest vertebrates." Proceedings of the National Academy of Sciences, 121(10)., Pp. 1-4.
[119] Knowlton, R. E., & Moutlon, J. M. (1963). "Sound Production In Snapping Shrimps Alpheus (Crangon) And Synalpheus." The Biological Bulletin., 125, Pp. 311-331.
[120] Everest, F.A., Young, R.W., & Johnson, M.W. (1948). "Acoustical Characteristics of Noise Produced by Snapping Shrimp." Journal Acoustical Society of America., 20(2), Pp. 137-142.
[121] Zuckerman, C. (2011). "SNAP, CRACKLE, POP." *National Geographic*, Washington, D.C., July 2011, P. 32.
[122] Callier, V. (2022). "Hard Knocks." Scientific American, 327(4), Pp. 12-14.
[123] Thompson, P. C. (2024) "STOMATOPODS: Why Is My Thumb Bleeding and My Mind Blown?" How to Influence Friends and Influence Fungi, C. Balakrishnan and M. Wasowski (eds.), St. Martin's Press, New York, pp. 17-20.
[124] Anon. "Snapping Shrimp Sounds (*Alpheus heterochaelis*)." University of Rhode Island and Inner Space Center, Accessed April 27, 2024.
[125] Hatch, L. (2021). "Oh Snap! What Tiny Shrimp Can Tell Us About Habitat Health." NOAA Office of National Marine Sanctuaries, https://sactuaries.noaa.gov>news>dec21>oh-snap accessed April 26, 2024.
[126] Schmitz, B., Versiuis, M., von der Heydt, A. & Lohse, D. (2000). "A unique way of sound production in the snapping shrimp (Alpheus heterochaelis), Journal Acoustical Society of America.,108, https://doi.org/10.1121/1.4743419, accessed April 26, 2024.
[127] Eriksson, L. J. (1999.) "A Brief Social History of Active Sound Control:, Sound and Vibration, 33(7), Pp. 14-17.
[128] Hirschorn, M., & Duda, J., (2000) "Is Social Acceptance a Problem for Noise Control and Active Silencers?" Sound and Vibration, 34(8), Pp. 26- 29.
[129] O'Connor, L. (1994). "Generating the sounds of silence." Mechanical Engineering, 116(4), Pp. 54-58.
[130] Posey, R. D. & Broyles, S. K. (1973). "Noise Control for Neighborhood Genset." *Electrical World*, March 15, 1973,
[131] Nelson, J. P. 1980. "Airports and Property Values, A Survey of Recent Evidence." Journal of Transport Economics and Polic*y*, January 1980, .Pp. 37-52.
[132] Nelson, J. P. 1982. "Highway Noise and Property Values: A Survey of Recent Evidence." Journal of Transport Economics and Policy, May 1982, Pp. 117-138.
[133] Nash, E. (2023]. The real pickleball wars are off the court, News.com.au, October 20, 2023.
[134] Margain, O. (2024). Pickleball precautions: Braintree trying to reduce sport's noise issues for neighbor: The sport has caused too much racket to residents in other cities and towns, including Weymouth, Falmouth, NBC Boston, March 14, 2024.
[135] Financial Samurai (2024). Quantifying Pickleball's Impact On Real Estate Prices: Mostly Negative, May 5, 2024.