THESIS

NOISE CHARACTERIZATION OF OIL AND GAS OPERATIONS

Submitted by

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ABSTRACT

NOISE CHARACTERIZATION OF OIL AND GAS OPERATIONS

In cooperation with The Colorado Oil and Gas Conservation Commission (COGCC), researchers at Colorado State University (CSU) conducted area noise monitoring at 23 oil and gas sites throughout Northern Colorado. The goals of this study were to: (1) measure and compare the sound levels for the different phases of oil and gas development sites; (2) evaluate the effectiveness of sound barriers; and (3) determine if sound levels exceeded the COGCC noise limits. The four phases of oil and gas development include drilling, hydraulic fracturing, completion and production. Sound measurements were collected using the A- and C-weighted scales. Octave band analysis was also performed to characterize the frequency spectra of the sound measurements.

Noise measurements were collected using noise dosimeters and a hand-held sound-level meter at specified distances from the development sites in each cardinal direction. Data were analyzed using descriptive statistics and a t-test was used to determine significant differences in noise levels for drilling sites with and without sound barriers. In addition, noise maps were developed to illustrate the behavior of the noise propagation.

At 117 yards, the sound-measurement distance specified by the COGCC noise rule, drilling, hydraulic fracturing, and completion sites without sound barriers exceeded the maximum permissible noise levels for residential and commercial zones (55 dBA and 60 dBA, respectively). In addition, drilling and hydraulic fracturing sites with sound barriers exceeded the maximum permissible noise level for residential zones. Production sites were within the COGCC permissible noise level criteria for all zones. At 117 yards from the noise source, all drilling, hydraulic fracturing and completion sites exceeded 65 dBC.

Current sound wall mitigation strategies reduced sound levels in both the A- and C-weighted scales. However, this reduction in noise was not sufficient enough to categorize drilling and hydraulic fracturing sites as compliant with the current COGCC noise regulations.

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CHAPTER 1: INTRODUCTION

One emerging environmental noise concern is noise related to oil and gas operations. The oil and gas industry is rapidly expanding across the United States. As a result of this advancement, oil and gas operation sites are being developed near communities and within city boundaries. Among other potential environmental concerns such as air and water quality, noise attributed to oil and gas operations is a significant and persistent concern that has proved to be difficult to manage. The state of Colorado established the Colorado Oil and Gas Conservation Commission (COGCC) in 1951 to protect mineral rights owners and to prevent the waste of oil and gas resources.(1) The COGCC promotes the responsible development of oil and gas natural resources in Colorado. The Commission also ensures that oil and gas exploration and production is conducted in a manner that protects the health, welfare and safety of the public and the environment. Each year, the COGCC responds to numerous complaints related to oil and gas activities. From 2008 through 2012, the COGCC received 1,175 complaints from Colorado residents. The most common complaint was about groundwater concerns with 439 complaints filed. The second most common complaint involved noise, which accounted for 10% (119) of total complaints.(2) Possible sources of noise attributed to oil and gas development includes truck traffic, drilling, hydraulic fracturing, completion activities, production well pumps and air compressors. These noise sources have different frequencies, durations, and overall sound pressure levels that make it difficult to control. The focus of this study is threefold. First, the Colorado State University researchers will characterize and compare the sound levels produced by the different phases of oil and gas development. Secondly, the effectiveness of sound barriers will be evaluated. Thirdly the researchers will determine if sound levels exceeded the current COGCC noise limits. A variety of oil and gas operations are not complying with the current

COGCC noise regulations in residential/agricultural/rural zones. The Colorado State University researchers served as an external third party to provide study results that could be used, in part, to amend the current COGCC Aesthetic and Noise Control Regulations if necessary.

Sound is a ubiquitous part of daily life and it can originate from a seemingly limitless number of sources. Society tends to tolerate a certain level of sound before it becomes a nuisance, distraction or health hazard. When a sound is unwanted, interferes with speech or communication or causes the potential for hearing impairment, it is classified as noise.(3) Noise problems can be classified into two major categories; occupational noise and community noise. Separate standards regulate each type of noise category. Community noise is unwanted sound that occurs outside of the workplace.(4) A community noise problem is dynamic in nature and can result from a combination of sources potentially affecting a large number of individuals. According to the Housing and Urban Development's (HUD) annual housing survey, approximately one-half of the survey participants thought noise was a significant issue in their neighborhood.(5)

CHAPTER 2: LITERATURE REVIEW

Sound is a pressure wave propagated through an elastic medium, such as air or water. Depending on pressure wave characteristics, sounds can have different pitches or frequencies. Sound can be created by vibrating materials, extreme expansion or compression of a medium (explosion or implosion), or vortex shedding. Vortex shedding occurs when a medium, such as air or water, rapidly flows past a blunt object, instead of traveling in a streamline with no interruptions. (6)

Physiology of the Human Ear

When a sound pressure wave interacts with the human ear, a cascade of interconnected events occur that enable humans to perceive sound. The human ear is comprised of three major parts; the outer ear, middle ear and inner ear. The outer ear is designed to capture and direct sound into the external auditory canal leading to the middle ear. The pinna and external auditory canal make up the outer ear. The pinna is the visible portion of the outer ear and is commonly called the "ear." The shape of the pinna is ideal for collecting sound waves and transferring them into the external auditory canal. The external auditory canal amplifies the sound as it travels toward the middle ear.(7)

The middle ear consists of the tympanic membrane or "eardrum," three auditory ossicles and the oval window. Sound waves travel through the external auditory canal and strike the eardrum. The eardrum vibrates and transfers energy to the three ossicles. The ossicles are three small bones named the incus, malleus and stapes.(7) These bones function as a "hammer" that puts pressure on the oval window when sound pressure waves contact them. The purpose of the middle ear is to transform sound waves into mechanical energy using the eardrum and ossicles. The mechanical force that travels through the ossicles is forced upon the oval window and the energy is transferred into the inner ear.(7) Without the middle ear's ability to efficiently transform sound energy, a significant portion of the original sound energy would be lost before it reached the inner ear.(7)

The inner ear is responsible for converting the energy transformed by the middle ear into a neural-electrical signal. The brain receives the electrical signals produced by the inner ear and interprets it as "sound." A structure called the cochlea is located in the inner ear within the temporal bone. The cochlea is filled with endolymph fluid that transfers energy from the middle ear and oval window.(7) The cochlea contains thousands of stereocilia "hair cells" that respond to the energy traveling through the endolymph fluid. Stereocilia are located on the basilar membrane of the cochlea. When specific sterocilia are stimulated, electrical nerve impulses are sent to the brain, allowing humans to interpret sound. The structure of the human ear is illustrated in Figure 1.

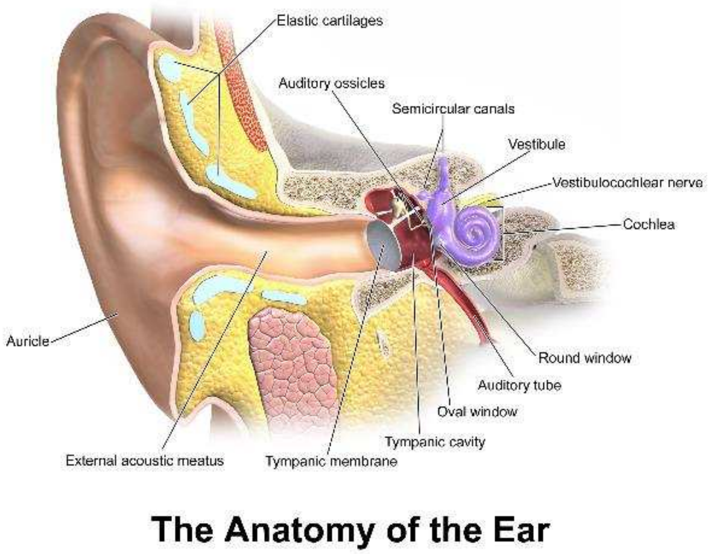


Figure 1: Structure of the Human Ear (Blausen Gallery, 2014)

Sound Wave Characteristics

The loudness of a specific sound depends on the amplitude of the sound pressure wave. The greater the amplitude is, the louder the sound volume. Sound levels are measured in decibels (dB). The decibel is based on a logarithmic scale that measures a ratio between two pressures.(7) Examples of common sources of sound and their decibel levels are shown in Table 1 below.(8)

Table 1: Common Sources of Sound and Associated Sound Pressure Levels (OSHA Technical Manual, 1999)

Environmental Sound Levels	dBA	Sound Levels at a Given Distance (Meters)
Threshold of Pain	135	
Typical Rock Concert	120	Jet Airplane (550m)
On Platform by Passing Subway Train	110	
	95	Jackhammer (15m)
	90	Compressor (8m)
	85	Heavy Truck (15m)
	80	Vacuum Cleaner (3m)
	70	Drilling Pump (152m)
Avg. Urban Area Background/Busy Office	60	Large Transformer (15m)
	55	Conversation (1m)
Urban Residence	50	
Small Town Residence	45	

Weighting Scales

Sound measuring devices use a microphone to respond to sound pressures. This response results in a specific sound pressure level (SPL) output. A SPL is the value reported when a sound measurement is collected. There are three different weighting scales used when measuring SPLs. The three scales are the A-, B-, and C- weighted scales.(9) The A-weighted scale filters sound pressures based on how the human ear responds to different sounds at varying frequencies. Relatively lower sound frequencies are de-emphasized using the A-weighted scale while the C-weighted scale incorporates lower frequencies as well as the higher frequencies. The human ear struggles to identify sounds of lower frequencies. Therefore, the A-weighted scale is used to estimate the response of human hearing and is considered an accurate representation of human hearing responses. A-weighted measurements are commonly used for regulatory purposes regarding worker health and hearing conservation. A comparison between A- and C-weighted readings can be used to determine if a noise source has a predominately low-frequency component or if it is predominately high-frequency noise. A noise source composed of mostly low-frequency elements is indicated when the C-weighted sound level is significantly larger than the A-weighted sound level. The B-weighted scale does not have many uses and is rarely utilized. An illustration of weighted scale responses between the three weighting scales for different frequencies is shown below in Figure 2.

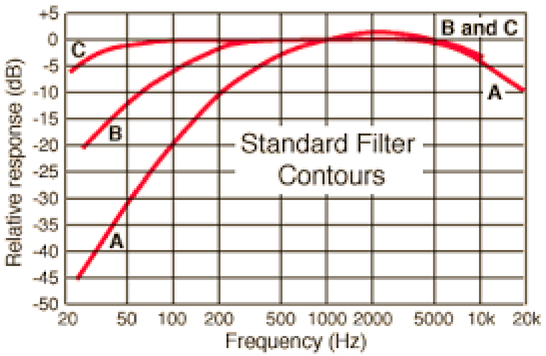


Figure 2: Sound Contour Filters (Hyperphysics, 2015)

<u>Sound Frequency</u>

In addition to fluctuating amplitudes that produce different "loudness" levels of sound, sound wave frequencies can also be dynamic. The frequency of a sound wave determines the pitch. Frequency is determined by the number of sound waves per cycle, and is measured in Hertz (Hz). The greater the frequency is, the higher the pitch of a certain sound. In other words, sounds with shorter wavelengths have a higher frequency, therefore resulting in a higher pitch. The human range for hearing is between 20 Hz and 20 kHz. The human ear responds most effectively to sounds with frequencies between 2kHz and 5kHz.(10) Sounds are rarely pure tones, but instead a mixture of various frequencies. Noise source frequencies can be analyzed by dividing the noise spectrum into specific frequencies "bands." This analysis is known as octave band analysis. Each octave band frequency from a noise source may have a SPL associated with it. Conversely, pure-tone noise sources may not have an associated SPL with each octave band. The higher the sound pressure level is for a frequency range, the more dominant that specific frequency range is in an individual measurement. This concept is illustrated in Figure 3 below. In Figure 3, 125- 250 Hz are the most dominant frequencies, indicating a potential low-frequency noise issue.

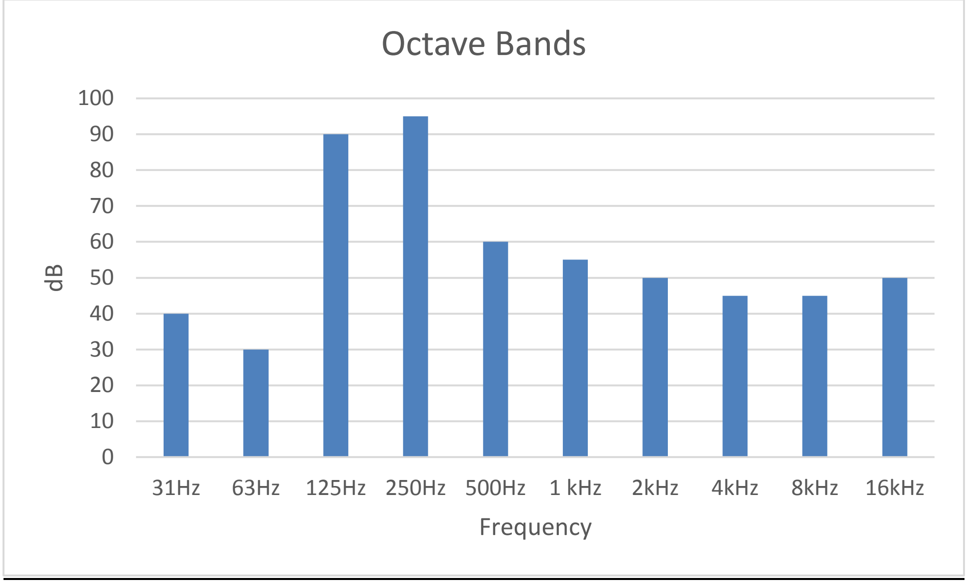


Figure 3: Octave Bands

Using octave band analysis, it is possible to identify the dominant frequency of a specific noise source, ultimately being able to determine if the source has predominantly high- or low-frequency characteristics.

Control Methods

It is essential to determine if a noise source has primarily high- or low-frequency characteristics as noise control methods can differ quite drastically. Low-frequency noise sources generate longer wavelengths and are able to travel greater distances and through materials that high-frequency noise cannot. There are a plethora of sound absorption, barrier and damping materials on the market that are designed to control specific frequencies of noise. Absorptive materials consume sound energy waves as opposed to reflecting the energy. (7) When sound waves are absorbed by absorptive materials, the sound energy is converted into heat. Different sound reducing materials are rated with absorption coefficients, or alpha values. Alpha values range from 0 to 1. Materials have different alpha values at different frequencies. An alpha value of 1 at a specific frequency indicates complete absorption of sound. An alpha value of zero means none of the sound is absorbed. If a material is proficient at absorbing low frequency noise, it may have an alpha value of 0.75 at 200Hz. Damping materials are used to effectively control vibrational energy due to noise. Damping materials help dissipate vibrational energy that causes equipment to rattle or knock. Sound barriers are another common form of noise control. Sound barriers come in numerous different forms and are designed to physically block the travel of sound waves to a specified receptor. Sound barriers are commonly used in the oil and gas industry as a form of noise control. A combination of damping, barriers and absorptive materials can be used to control complex noise issues. Different categories of noise control materials are better at controlling different types of noise. It is important to determine the frequency signature of the noise source in order to select an effective control material.

Considering that A-weighted sound levels are an accurate representation of the human hearing response, there are regulations governing permissible sound levels that utilize the A-weighted scale. According to the Occupational Safety and Health Administration (OSHA), the permissible exposure limit (PEL) for noise is 90 dBA as an eight-hour time-weighted average (TWA). That is, if an employee is exposed to sound levels greater than 90 dBA for a period of more than 8- hours, there is an increased risk for noise-induced hearing loss.(11) While there are detailed regulations protecting individuals exposed to noise measured on the A-weighted scale, there are no regulations governing employee protection against noise measured on the C-weighted scale. Limited research has been done to address low frequency noise and its potential health effects. However, low frequency noise has been observed to disrupt an individual’s overall circadian rhythm, may affect sleep or mood and can initiate a sense of vertigo in susceptible individuals.(12)

Community Noise

Noise is generally classified into two classes: occupational noise and community noise. The area of occupational noise involves protecting worker health and well-being in regards to exposures to potentially high levels of noise in the workplace. While occupational noise is an integral part of occupational health and safety, this study focused on the often overlooked, but equally as important topic of community noise. Community noise, also called environmental noise, is noise that affects people outside of the workplace. Common sources of community noise include traffic/transportation noise, construction, neighborhood noise sources and noise generated by industry that affects the public. Excessive noise can impact the public in many ways. In addition to annoyance, excess noise can cause speech interference, affect individuals' sleep and even impact their general quality of life. In extreme cases, high levels of environmental noise can aggravate pre-existing health conditions, decrease property values and trigger significant stress. Long-term exposure to high levels of noise outside of the workplace can result in sociocusis which is irreversible hearing loss as a result of everyday noises.(13) If an individual lives in a noisy community for an extended period of time, she or he may develop sociocusis.(13)

Unlike occupational noise regulations, community noise regulations are quite diverse. The Noise Control Act of 1972 granted states and individual cities the right to draft their own community noise rules, resulting in this diversity.(14) Community noise regulations are drafted in such a way that often times it is difficult for industries to comply with differing regulations if they have operations stationed in separate cities or states. Citizens have the right to protect their communities from excessive noise, therefore it is important for commercial and industrial operations to have a thorough understanding of community noise sources and regulations.

Through community noise regulations, citizens have the right to report potential noise infractions and establish a process for addressing the complaints.(14)

Community noise is commonly measured in equivalent continuous sound pressure levels (L_{eqs}) that are average sound levels collected over a specified time period. Community sound regulations are drafted so that permissible sound levels are higher during the daytime hours than at night. Individual L_{eqs} can be combined to produce a day-night average sound level (DNL). The DNL is the average sound level throughout a 24- hour time period. The DNL takes into account the daytime average sound level (7a.m. to 10p.m.) as well as the nighttime average sound level (10 p.m. to 7a.m.). Calculating the DNL is outlined in the following equation.(7)

$$L_{dn} = 10 \log (1/24 (15 (10^{Ld/10}) + 9 (10^{((Ln + 10)/10)}))$$

Where,

L_{dn} = day-night sound level (dB_A)

L_d = daytime equivalent sound level (dB_A)

L_n = nighttime equivalent sound level (dB_A)

Federal agencies such as the Environmental Protection Agency (EPA) use DNLs as a baseline for community noise guidelines. A common DNL that the EPA recommends is 55 dBA, meaning that the average daytime and night-time noise level should not exceed 55 dBA. Community noise ordinances commonly address noise issues based solely on the A- weighted scale. However, emerging public concern regarding C-weighted noise issues is compelling regulators to take notice. The COGCC is receiving an increased number of complaints unique to low frequency noise generated by oil and gas operations. Regulators like the COGCC are interested in incorporating a more elaborate section regarding low frequency noise in the C-weighted scale in new regulations. Community noise ordinances usually set noise limits for residential areas between 55 to 60 dBA during the daytime and 50 to 55 dBA at night.(15) Each community noise ordinance has the potential to be different, but sound measurements are generally collected at the property line of a complainant's residence.(14)

There are numerous factors that affect sound propagation in an outdoor setting. Acoustically, as the distance between a noise source and a receptor increases, the intensity of the sound at the receptor decreases. A general rule of thumb is when the distance between a source and receiver doubles, the sound pressure level decreases by 6 dB.(7) If a sound pressure level at a measured distance is known, it is possible to calculate an estimated sound pressure level at a second distance assuming the sound is traveling in a free field with no attenuation. There are no reflections in a free field and sound pressure waves radiate freely in all directions.(7) This concept is illustrated in Figure 4.

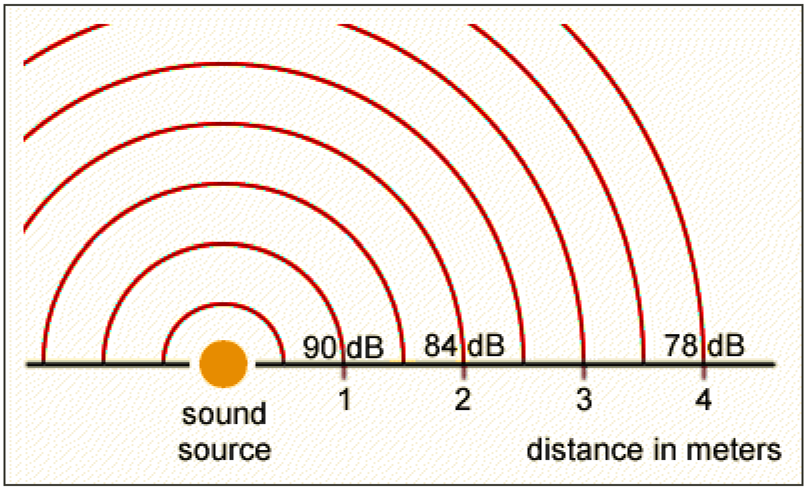


Figure 4: Inverse Square Law Concept in Free Field (OSHA, 2015)

The reduction in sound over a given distance can be estimated using the inverse-square law as illustrated in the following equation.

$$SPL_2 = SPL_1 + 20\log(d_1/d_2)$$

Where,

d_1= Distance 1
d_2= Distance 2
SPL_2= Sound pressure level at distance 2
SPL_1= Sound pressure level at distance 1

In the realm of environmental noise monitoring, free fields are rarely encountered. Commonly, natural and man-made barriers such as buildings or foliage exist that impede the travel of sound. Environmental variables including temperature, relative humidity and wind speed also affect how sound travels through the air. The speed of sound is directly related to square root of temperature. As air temperature decreases, the speed of sound decreases.(7) As the speed of sound decreases, the attenuation of the sound greatly increases with distance. There are also four attenuation factors that affect how noise travels. The four factors are: geometrical divergence, air attenuation, environmental attenuation and miscellaneous attenuation. Components that make up these factors include foliage, water, wind, humidity, and distance from the noise source. In addition to foliage and other ground surface characteristics, snow tends to dampen sound energy resulting in greater attenuation with increasing distance.(7)

In order to conduct an environmental sound survey, certain requirements must be met to ensure data integrity. Environmental factors such as those discussed above must be taken into account and addressed, if possible. For instance, the U.S. Department of Transportation recommends that sound measurements not be collected on snow-covered ground because snow acts as a damping material and increases attenuation. Weather conditions must be recorded and sound measurements should not be collected if wind speeds exceed approximately 12 miles per hour.(16) Wind generates noise when interacting with the microphone, thus interfering with the measurement. A wind screen placed on the microphone protects against this error to a certain extent however it is still recommended that sound measurements are not to be collected when wind speeds exceed 12 miles per hour. To avoid interference with the ground, it is recommended that the sound measuring device be placed approximately five feet above the ground surface. In addition, measurement locations should be free from significant ambient noise sources such as high volume roadways or other unwanted noise sources.

There are multiple instruments that can be used to perform environmental noise monitoring. Commonly, integrating sound-level meters (SLMs) are used to collect sound data over a certain period of time. These SLMs are able to record and store a conglomeration of sound level data in both the A- and C- weighted scales. There are three classes of SLMs; type zero, type one and type two SLMs. The three types are classified by their accuracy. Type zero SLMs are primarily used in laboratory settings. Type one meters are precision grade with an accuracy of +/- 1 dB. Type two meters are classified as general-purpose devices that have an accuracy of +/- 2 dB. Type two meters meet the minimum requirements mandated by OSHA and are commonly used in work environments.(17) Some SLMs are equipped with octave band analyzers used to evaluate the frequency spectrum of a noise source. Specific noise dosimeters can also be used to collect environmental noise data if they meet the required ANSI standard S1.4-1983 for a sound-level meter.(18) Dosimeters are usually used to monitor employee noise exposure dose over time, however some dosimeters can also function as sound-level meters. Using appropriate dosimeters can be a cost-effective way to measure environmental noise.

Process Description

Once an oil and gas site is established, the site is active 24/7 until operations are complete. After construction, drilling, hydraulic fracturing and completion, a well site is used for production. Drilling and hydraulic fracturing are two completely separate processes. During the drilling phase, a specialized drilling rig drills a hole anywhere between 4,000 and 10,000 feet depending on the type of well and the depth of the oil reservoir.(19) After the hole is drilled, casing and cement are pushed through the well to seal it and prepare the well for the hydraulic fracturing phase. During the hydraulic fracturing phase, large trucks and specialized machinery pump hydraulic fracturing fluid, comprised of mostly sand and water, into the hole created during the drilling phase. The hydraulic fracturing fluid is pumped at 10,000 psi more than a mile below the surface.(20) The high pressure fluid is pumped into the well to separate (fracture) the shale rock structure to stimulate the release of natural gas or oil. Depending on the number of wellheads at a specific site, it may take a few days to several weeks to complete the hydraulic fracturing phase.(21)

Production is the longest phase of oil and gas development and involves the process of recovering and isolating hydrocarbons from the mixture of other liquid and solid constituents.(22) Wells may continue to produce hydrocarbons for decades. After separation, the isolated hydrocarbons are transported via pipelines or by tanker trucks. At production well sites, there are large separators used to separate the valuable hydrocarbons. These separators produce a constant low frequency noise when in operation. The number of separators at a production facility can vary; a large site may have over 20 separators while a smaller site may have three. In addition to separators, pumpjacks can be located on production sites. Pumpjacks are used to mechanically pump fluid out of a well if there isn't sufficient pressure for the liquid to flow to the surface on its own. Pumpjacks can be a significant source of noise at production sites.(23) It is important to characterize these noise sources at the different types and sizes of oil and gas sites in order to provide affected or concerned parties with accurate and reliable information.

Each phase of oil and gas development has different contributing noise sources. Drilling and hydraulic fracturing operations have large air compressors, generators and engines that power the drill rig and hydraulic fracturing equipment. These compressors, generators and engines contribute the most noise to drilling and hydraulic fracturing sites. Drilling operations also have mud pumps on site that are used to circulate drilling fluid. Mud pumps on drilling sites can be a substantial noise source. Truck traffic may contribute a significant amount of noise in every phase of oil and gas production.

In an attempt to mitigate noise produced by drilling and fracturing operations, oil and gas operators commonly install sound barriers or sound walls to control the noise. These barriers range from 16 to 32 feet in height. The barriers are commonly constructed from eight foot high by 20-foot long acoustic blankets that are mounted on steel frames but some operators choose to use hay bales. The acoustic blankets are rated at a sound transmission class (STC) of – 25 and are designed to reduce equipment noise levels by 15 to 22 dBA.(24) While collecting sound measurements, it is important to consider the "sound shadow" that is produced by the installation of these sound walls. The sound or acoustic shadow is an area where acoustic waves do not propagate due to an obstruction such as a sound wall. The acoustic shadow results in decreased sound pressure levels within the shadow. In the scenario involving sound walls, the sound waves can be absorbed by the barrier as well as reflected back and diffracted around the barrier. The concept of an acoustic shadow is illustrated in Figure 5.

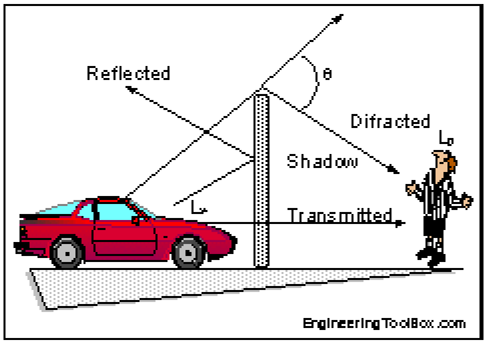


Figure 5 Acoustic Shadow (Engineering Toolbox, 2016)

A proportion of sound waves can also be transmitted through the sound wall barrier depending on the frequency of the sound. While collecting measurements outside of the perimeter of a sound wall, it is important to take measurements outside of the acoustic shadow to ensure accuracy. The size of the acoustic shadow can vary depending on the frequency of the noise source. Typically, lower frequency noises aren't diffracted as sharply of an angle towards the ground as higher frequency noise, resulting in a larger shadow.(25) The effectiveness of a sound wall is dependent on the frequency of the sound. In order to be effective, the sound wall must be significantly larger compared to the wavelength of the sound. If the sound wall is too short, diffraction of the sound will occur ultimately limiting the effectiveness of the wall.(25) The attenuation of sound due to a sound wall installation can be modeled using the Fresnel equation. The Fresnel equation is a relationship between a Fresnel number, the wavelength of sound and path length difference. The variables in Figure 6 can be used to describe the Fresnel equation.

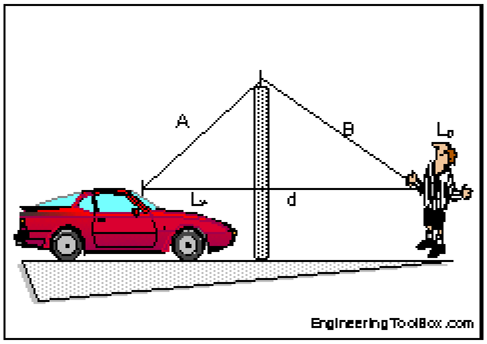


Figure 6 Fresnel Concept (Engineering Toolbox, 2016)

The Fresnel equation is as follows:

$N = 2d^{*} / \lambda$

Where: N *= Fresnel Number*

$d^{*} = A + B - d$

λ *= wavelength*

d^{*} represents the path length difference. When A,B, λ and the Fresnel number are known, the equation can be used to predict the approximate length of the sound shadow (d). As the Fresnel number increases, the barrier attenuation increases. This concept is illustrated in Figure 7.

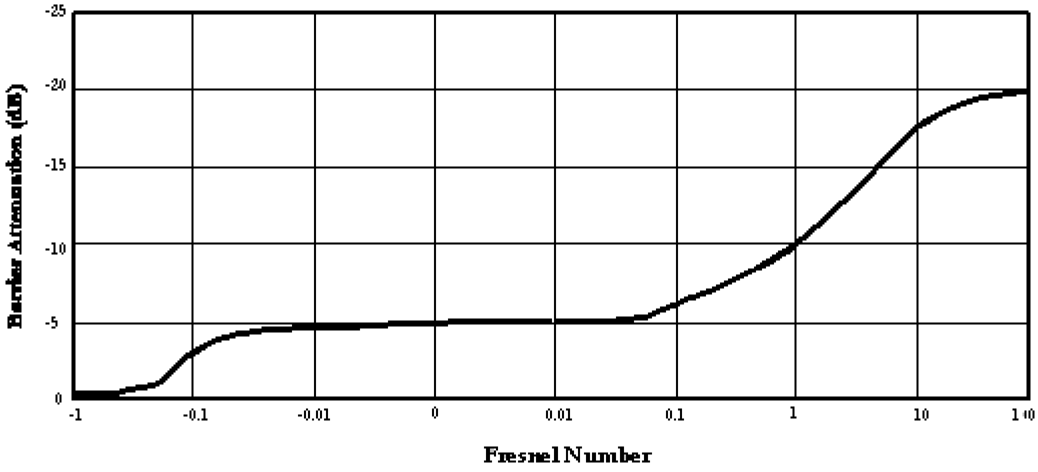


Figure 7 Fresnel Number Related to Attenuation (Dept. of Transportation, 2016)

Oil and gas well sites and production facilities can be located in several zoning areas. The zoning areas include residential/agricultural/rural, commercial, light industrial or industrial. In Colorado, each zoning area has an associated maximum permissible noise level at a distance of 117 yards from the noise source. These limits are set forth by the current COGCC aesthetic and noise control regulations. The current maximum permissible noise levels for each zone are shown in Table 2.(26)

Table 2: COGCC Noise Zone Regulations

Zone	**7:00 am to next 7:00 pm**	**7:00 pm to next 7:00 am**
Residential/Ag./Rural	55 dB(A)	50dB(A)
Commercial	60 dB(A)	55dB(A)
Light Industrial	70 dB(A)	65dB(A)
Industrial	80 dB(A)	75dB(A)

Oil and gas operations must comply with the maximum permissible noise levels mandated for the specific zone. In response to a noise complaint, COGCC regulations require that sound levels be measured at a distance of 350 feet from the noise source. If the oil and gas site is located closer than 350 feet from an existing occupied structure, sound levels shall be measured 25 feet from the structure toward the noise source.(26) If sound level measurements at 350 feet are impractical due to topography, measurements can be taken at a lesser distance and can be extrapolated to a 350-foot equivalent using the inverse square law for noise. The COGCC noise control regulations also briefly address C-weighted sound pressure levels. According to the COGCC noise standard, if a measurement collected 25 feet from a residence exceeds 65 dBC, further action must be taken to reduce low frequency noise. It has been suggested that below 65 dBC, vibrational issues are minimized and the majority of people don't experience an annoyance or unwanted disturbances from low frequency noise.(27)

Relevant Studies

La Plata County Study

La Plata County employees conducted an environmental noise study in 1998 that evaluated the sound levels of potential noise sources at oil and gas sites. The investigators collected sound level measurements at various distances from different oil and gas equipment during different phases of oil and gas exploration and reported the results. The results of the La Plata County study are illustrated in Table 3.(28)

Table 3: La Plata County Study Results

Source	Measured Sound Level (dBA)	Measurement Location
Compressor	50	375 feet from property line
Pumping Units	50	325 feet from well pad
Fuel and Water Trucks	68	500 feet from source
Crane for Hoisting Rigs	68	500 feet from source
Pump Used During Drilling	62	500 feet from source
Average Well Construction	65	500 feet from source

It is important to note that this study took place in 1998. It is likely that oil and gas equipment and technology has changed since that time period, potentially altering the sound levels. In addition, this study only addressed noise levels in the A-weighted scale.

Fort Worth Study

Behrens and Associates evaluated the noise mitigation efforts in Fort Worth, Texas (2006) at three different oil and gas sites by measuring sound levels. First, background pre-drilling sound levels were collected at four potential drilling sites throughout the city of Fort Worth to determine the ambient sound levels at a typical drill site in the area. Background sound levels ranged from 48 to 67 dBA. After background sound levels were obtained, sound levels were measured at three drilling sites during different parts of drilling operations. The chosen sites were initially unmitigated. Sound levels were measured before and after mitigation at each site. The drilling rigs were 1000 horsepower rigs and considered to be a typical size for drilling rigs in the Fort Worth area. The sound levels were measured in each cardinal direction with measurable noise recorded up to 700 feet from the drilling rig in some cases. The average drilling sound level was 71 to 79 dBA at 200 feet from the drilling rig. Several mitigation systems were installed at the drilling sites. Twelve-foot drilling rig acoustic barriers were installed on the rig floor around three sides of the rig. This mitigation technique reduced the sound level at 200 feet from the drilling rig on average from 72-77 dBA to 64-68 dBA. Enhanced drilling rig mufflers were installed on drilling rig engines and generators. This mitigation resulted in an average sound level decrease of 1.5 dBA ten feet from the engine or generator. Finally, drilling rig perimeter sound walls were installed. A 16 foot high STC-25 Acoustical Blanket Sound Wall was installed on the east side of a drilling rig located near a neighborhood. During operation, the drilling rig’s sound level 50 feet from the rig, located between the rig and the sound wall, was 80dBA. The sound level 20 feet outside the sound wall, located 120 feet from the rig, was 62 dBA. The researchers concluded that with proper mitigation in place, maximum daytime drilling noises of 59 dBA and maximum nighttime drilling noises of 51 dBA at 200 feet from the drilling rig could be achieved. (29) The measurements collected in this study only addressed sound levels in the A-weighted scale.

COGCC Study

In addition to Colorado State University’s noise data, the COGCC collected several sound measurements from oil and gas sites in 2015. The COGCC was interested in obtaining 24-hour measurements in both the A-weighted and C-weighted scales. Sixteen drilling and hydraulic fracturing locations were evaluated using A-and C-weighted measurements. Mitigated and unmitigated sites were evaluated. In this specific scenario, mitigated refers to sites that had sound wall installations in place. Measurements were collected 350 feet from the major noise source. The results from the COGCC evaluations compared with results from the Colorado State University researchers are presented in Tables 4 and 5.

Table 4: Mean C-Weighted Sound Levels

Site Type	**COGCC Study Mean Sound Level (dBC)**	**CSU Study Mean Sound Level (dBC)**
Unmitigated Drill Site at 350 feet	76	79
Mitigated Drill Site at 350 feet	72	73
Unmitigated Fracturing Site at 350 Feet	80	80
Mitigated Fracturing Site at 350 Feet	76	74

Table 5 Mean A-Weighted Sound Levels

Site Type	COGCC Study Mean Sound Level (dBA)	CSU Study Mean Sound Level (dBA)
Unmitigated Drill Site at 350 feet	62	65
Mitigated Drill Site at 350 feet	54	59
Unmitigated Fracturing Site at 350 Feet	69	70
Mitigated Fracturing Site at 350 Feet	59	59

Based on the COGCC data presented, there was a 4 dB decrease in c-weighted noise between unmitigated and mitigated drilling and hydraulic fracturing sites. Regarding A-weighted noise, there was a reduction of 8 dB between unmitigated and mitigated drilling sites while there was a reduction of 10 dB between unmitigated and mitigated hydraulic fracturing sites. Based on the Colorado State University data, there was a 6 dB decrease in C-weighted noise between unmitigated and mitigated drilling and hydraulic fracturing sites. For A-weighted noise, there was a 6 dB reduction between unmitigated and mitigated drilling sites and an 11 dB reduction between unmitigated and mitigated hydraulic fracturing sites. In both COGCC and Colorado State University data, there was a greater reduction in A-weighted noise than C-weighted noise when sound walls were in place.

CHAPTER 3: PURPOSE AND SCOPE

Purpose

The purpose of this study was to analyze and characterize the noise levels associated with the four phases of oil and gas operations using a sound-level meter (SLM)/octave-band analyzer (OBA) and noise dosimeters. The four phases that were assessed included drilling, hydraulic fracturing, completion and production. Drilling and fracturing operations often use sound wall installations as a noise mitigation technique. Sound measurements from drilling and fracturing sites with and without sound wall installations were collected to assess the effectiveness of the sound walls. The results of this study were provided to the Colorado Oil & Gas Conservation Commission (COGCC) and may be used as the technical background in revising the COGCC's Aesthetic and Noise Control Regulations.

Research Questions

The evaluation of the four phases of oil and gas production will be used to answer the following:

1. Is there a significant difference in noise levels between the four phases of oil and gas operations?

2. Are current mitigation practices sufficient to provide community protection from excessive sound levels?

3. Do the sound levels exceed current COGCC limits?

Scope

The scope of this research was to measure the noise levels from the four phases of oil and gas operations, to determine the effectiveness of sound barriers and examine if oil and gas operations exceeded the current COGCC noise limits. A statistical two-sample t-test was conducted to determine if there was a significant difference in sound levels between drilling sites with and without sound wall installations. For the statistical analysis, the null hypothesis was that there is not a significant difference in reduction of noise measurements between drilling sites with and without sound wall installations. Or in other words, there is no significant difference between the mean SPL for drill sites with and without sound wall installations. Additionally, the results of this study may provide COGCC officials with information that can be used to amend the current COGCC noise regulations if necessary.

CHAPTER 4: METHODS AND MATERIALS

The Colorado State University researchers cooperated with the COGCC to obtain access to oil and gas sites for sampling. Area noise sampling was conducted at 23 oil and gas sites between November 2014 and March 2015. COGCC employees accompanied the CSU researchers on site with site employees. Only sites with low ambient background noise as possible were selected. The researchers carefully selected sites away from major roadways or potentially noisy industrial areas. As a result, the number of acceptable sites that were selected were limited. The selected sites were located along the front range of Northern Colorado, ranging from the towns of Firestone to Kersey. Sampling locations included sites owned by various operators. The researchers didn't target sites owned by specific operators. The identity of the operator at each site was irrelevant as the goal of this research wasn't to evaluate noise levels at oil and gas sites based on the operator.

Four Larson Davis noise dosimeters (Spark model 706RC) and a Larson Davis model 824 handheld sound-level meter/octave band analyzer (SLM/OBA) were used to collect noise samples at each oil and gas site. The Larson Davis SLM/OBA is a type one meter, meaning that it has an accuracy of +/- 1 dB. The Larson Davis noise dosimeters meet the American National Standards Institute Standard ANSI S1.4, 1983 specifications for Sound-level meters. The noise dosimeters are type two meters, meaning that they have an accuracy of +/- 2 dB. Sound level measurements were collected using the A and C weighting scales, slow response, and a three-decibel exchange rate. Using the SLM, octave band analysis was performed to identify the major frequency noise levels at each site. Given the variability between the same types of sites, at least three representative surveys for each type of site, except for completion sites, were taken. Due to a limited number of available completion sites that met the criteria, only two completion sites were sampled. Four dosimeters with tripods at a height of five feet were placed 117 yards (350 feet) from the most significant noise source in each cardinal direction. The height of five feet was chosen per procedures outlined in *The Noise Manual* (E.H. Berger, 2003). The most significant noise source was centrally located at each oil and gas site and included the machine or group of machinery that contributed the greatest amount of noise originating from the site. The distance of 117 yards was based on the current COGCC Aesthetic and Noise Control Regulations. The dosimeters collected sound level measurements the entire time the researchers were on site. Data were collected on the dosimeters from anywhere between 20 and 45 minutes. After collecting data from the field, the researchers used Larson Davis Blaze software to obtain the 15-minute time period where the sound levels were the highest. The data were used to model a 15-minute average "worst-case" sound level at a given site. Before collecting sound level measurements, the researchers met with oil and gas personnel on site to ensure the site was operating at maximum capacity. To obtain "worst-case" sound level measurements, researchers collected measurements while operations at the site were running at 100%. The SLM/OBA was used to collect five-second L_{eqs} at various distances from the noise source in each cardinal direction. The average of the 15-minuteL_{eqs} and five minute L_{eqs} were calculated for each site and compared to COGCC regulations. In ideal circumstances, measurements were collected at approximately 117 yards (350 ft), 58.5 yards, 29 yards, 14 yards, and as close as possible from the most significant noise source in each cardinal direction. A Nikon 550 Rangefinder (Tokyo, Japan) was used to precisely record the distances of measurement points. Measurement points are illustrated in Figure 8.

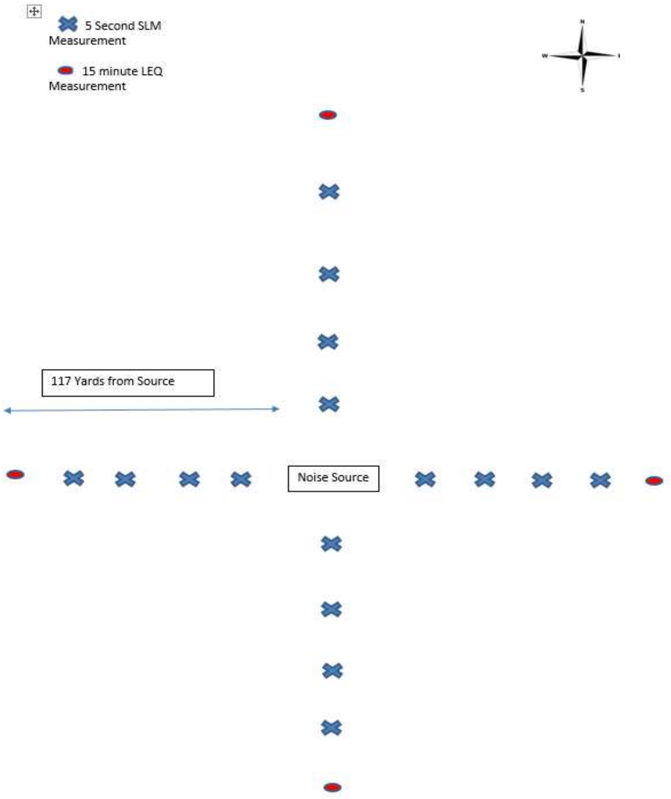


Figure 8 Illustration of Measurement Collection Points

In addition to unmitigated sites, sound measurements were collected at three drilling sites and one fracturing site with sound wall mitigation in place. These sites had the same sound wall mitigation which included sound blankets mounted on a steel frame. At these sites, measurements were collected inside and outside of the sound walls. Using the SLM, five second L_{eq} measurements were collected inside the wall beginning at 10 feet from the inside of the wall and halving the distance until the researchers could collect measurements as close as possible to the noise source in each cardinal direction. The length of five seconds for L_{eq} measurements collected using the SLM was chosen per procedures outlined in *The Noise Manual* (E.H. Berger, 2003). Fifteen-minute L_{eq} measurements were also collected 10 feet from the inside of the wall in each cardinal direction. At a distance of 117 yards in each cardinal direction outside of the sound walls, researchers collected 15-minute L_{eq} measurements. In order to avoid the acoustic shadow created by the 32 foot-tall sound walls, a distance of 117 yards from the walls was chosen. It was observed through trial measurements that sound measurements collected within 100 yards outside of the sound wall had the potential to be skewed due the acoustic shadow. At several sites, the site orientation and operating equipment were located in such a way that these exact distances could not be achieved. For example, on some sites the researchers were limited on how close they could get to the noise source due to safety factors. Measurements were collected using the same protocol for mitigated sites as unmitigated sites to allow for data comparison between the two types of sites. The noise monitoring instruments were pre- and post-calibrated at 94 dB and 114 dB to maintain data quality and assure accuracy.

Noise measurements were collected when oil and gas machinery and equipment was fully operational. It was important to collect data during the loudest part of each phase to model “worst-case” noise level scenarios. Before conducting the noise sampling, environmental factors including temperature, humidity and wind speed were recorded at each site as these factors may influence the noise levels. Data were not collected when temperatures were below 20°F or when the wind speed exceeded 10 miles per hour (mph). In addition, sound measurements were not collected when there was snow present on the ground as snow can affect sound propagation.

Global positioning system (GPS) coordinates were recorded for each individual measurement location. GPS coordinates were collected to develop sound contour maps of each site if feasible. Using the inverse square law for sound, the data from these measurements were extrapolated to further distances. In addition, noise contour maps were generated using the Noise at Work noise-mapping software. Contours of potential zones of non-compliance are shown on the maps. The maps can be used to identify areas where a residence or business may be located and whether or not it is at risk for excessive noise.

A statistician at the Statistical Consulting Laboratory at Colorado State University was consulted to determine an acceptable sample size of sites before sampling took place. The statistician concluded that due to the unique characteristics of the study and lack of previous data available, it would be best to sample as many sites that were available to sample. In total, 23 acceptable oil and gas sites were sampled. The types and number of sites that were sampled is shown in Table 6.

Table 6 Site Sample Breakdown

Site Type	Number of Sites Sampled
Drill Sites without Sound Walls	4
Drill Sites with Sound Walls	3
Fracturing Sites without Sound Walls	4
Fracturing Sites with Sound Walls	1
Completion Sites	2
Production Sites	9

It was difficult to find active oil and gas sites for sampling that met the inclusion criteria. The majority of sites with sound wall installations were located in heavily urbanized areas with significant amounts of background noise. This resulted in a limited sample size for hydraulic fracturing sites with sound wall installations and completion sites.

All data were downloaded and analyzed using Larson Davis Blaze Software as well as Noise at Work Software. This software was used to describe acoustic measurements including mean L_{eq} and octave band noise levels during each phase. The Noise at Work Software was used to develop visual representations of noise levels at different oil and gas operation sites. The noise data were compared to the maximum permissible noise levels for each land-use zone as stated in the COGCC Aesthetic and Noise Control Regulations. A two-sample t-test was conducted using Statistical Analysis System (SAS) statistical software for drill sites with and without walls. A t-test was not used on hydraulic fracturing site data due to the limited sample size. The researchers were able compare mean sound levels and determine if there was a statistically significant difference in sound levels between drill sites with and without walls.

CHAPTER 5: RESULTS AND DISCUSSION

Five-second and 15-minute equivalent sound pressure levels (L_{eq}) were collected 117 yards (350 feet) from the noise source at each site using the A- and C-weighted scales. On average, completion, drilling and hydraulic fracturing sites without walls exceeded the maximum permissible A-weighted noise level for residential and commercial zones. On average, drilling and hydraulic fracturing sites with walls exceeded the maximum permissible A-weighted noise level for residential zones. The majority of production sites stayed within the maximum permissible A-weighted noise level for all zones. Average 15-minute L_{eqs} at 117 yards for each type of oil and gas site were compared to the current COGCC regulations. These comparisons are illustrated in Table 7. The number and type of sites that exceeded current COGCC regulations can be determined by using Table 7. The COGCC regulations are separated into zones between the hours of 7am to 7pm as well as 7pm to 7am. Each zone has a specific permissible sound level indicated in parenthesis in the table. The percentage of sites that exceeded the permissible sound level for each zone are shown in the subsequent columns categorized by site type.

Table 7 COGCC Noise Levels Percent Exceedance

Zone / COGCC dBA Limits Exceeded	COGCC Noise Levels Percent Exceedance at 117 Yards					
	Drilling Sites No Walls	Drilling Sites with Walls	Completion Site	Fracturing Sites No Walls	Fracturing Site with Walls	Prod. Sites
Residential (55dBA) 7am to 7pm	4/4 (100%)	3/3 (100%)	1/1 (100%)	4/4 (100%)	1/1 (100%)	2/9 (22%)
Commercial (60 dBA) 7am to 7pm	4/4 (100%)	1/3 (33%)	1/1 (100%)	4/4 (100%)	0/1 (0%)	0/9 (0%)
Light Industrial (70 dBA) 7am to 7pm	0/4 (0%)	0/3 (0%)	0/1 (0%)	2/4 (50%)	0/1 (0%)	0/9 (0%)
Industrial (80 dBA) 7am to 7pm	0/4 (0%)	0/3 (0%)	0/1 (0%)	0/4 (0%)	0/1 (0%)	0/9 (0%)
Residential (50 dBA) 7pm to 7am	4/4 (100%)	3/3 (100%)	1/1 (100 %)	4/4 (100%)	1/1 (100%)	3/9 (33%)
Commercial (55 dBA) 7pm to 7am	4/4 (100%)	3/3 (100%)	1/1 (100%)	4/4 (100%)	1/1 (100%)	2/9 (22%)
Light Industrial (65 dBA) 7pm to 7am	3/4 (75%)	0/3 (0%)	0/1 (0%)	4/4 (100%)	0/1 (0%)	0/9 (0%)
Industrial (75 dBA) 7pm to 7am	0/4 (0%)	0/3 (0%)	0/1 (0%)	0/4 (0%)	0/1 (0%)	0/9 (0%)

On average, C-weighted noise levels at production sites were 64 dBC. Three of the nine production sites sampled were at or above 65 dBC. At 117 yards from the noise source, every drilling, hydraulic fracturing and completion site exceeded 65 dBC. Five-second and 15-minute L_{eq} results for drilling, hydraulic fracturing, completion and production sites are illustrated in

Tables 8 through 13. The sound data for individual sites as well as overall averages are included in these tables. On average at a distance of 117 yards from the noise source, including all four cardinal directions;

- The A-weighted 15-minute L_{eq} data for drilling sites without walls were 5 dBA lower than hydraulic fracturing sites without walls.
- The C-weighted 15-minute L_{eq} data for drilling sites without walls were 1 dBC lower than hydraulic fracturing sites without walls.
- The A-weighted 15- minute L_{eq} data for drilling sites with walls were the same as the hydraulic fracturing site with walls.
- The C-weighted 15 -minute L_{eq} data for drilling sites with walls were 1 dBC lower than the hydraulic fracturing site with walls.
- The average A-weighted sound level measurements collected at production sites were at least 15 dBA lower than the A –weighted 15- minute L_{eq} measurements collected at drilling, hydraulic fracturing and completion sites.

It is important to note that Site 13 was configured in such a way that sound measurements could not be collected at 117 yards from the most significant noise source. Due to site configuration, sound measurements were collected between 44 and 77 yards from the most significant noise source in each cardinal direction. As a result, the average sound measurements between the two completion sites could not be compared to one another. Additionally, only 5-second L_{eq} measurements from the SLM were obtained from production sites. The sound levels at production sites were below the gain detection settings for the noise dosimeters that were used to collect 15-minute L_{eq} measurements. The gain was adjusted to 20 dB that limited the instrument's measurement range from 53 dB to 123 dB. Sound levels lower than 53 dB were not collected by noise dosimeters.

Drilling Sites

Table 8 Noise Levels at Drilling Sites without Walls (117 Yards from source)

Site	**5 Second Leq dBA**	**5 Second Leq dBC**	**15 minute Leq dBA**	**15 minute Leq dBC**
1	64	78	64	79
2	64	80	63	79
3	66	80	65	80
4	64	77	65	No Data
Average	**65**	**79**	**65**	**79**

Table 9 Noise Levels at Drilling Sites with Walls (117 Yards from source)

Site	**5 Second Leq dBA**	**5 Second Leq dBC**	**15 minute Leq dBA**	**15 minute Leq dBC**
5	58	75	60	76
6	58	73	56	70
7	52	67	59	69
Average	**57**	**73**	**59**	**73**

Hydraulic Fracturing Sites

Table 10 Noise Levels at Hydraulic Fracturing Sites without Walls (117 Yards from source)

Site	5 Second Leq dBA	5 Second Leq dBC	15 Minute Leq dBA	15 Minute Leq dBC
8	65	79	66	79
9	69	80	72	82
10	66	77	66	77
11	72	82	70	81
Average	**69**	**80**	**70**	**80**

Table 11 Noise Levels at Hydraulic Fracturing Sites with Walls (117 Yards from source)

Site	5 Second Leq dBA	5 Second Leq dBC	15 Minute Leq dBA	15 Minute Leq dBC
12	59	73	59	74

Completion Sites

Table 12 Noise Levels at Completions Sites without Walls at 44-77 and 117 Yards From Source

Site	**5 Second Leq dBA (No. of measurements)**	**5 Second Leq dBC (No. of measurements)**	**15 Minute Leq dBA (No. of measurements)**	**15 Minute Leq dBC (No. of measurements)**
13	73 (4)	82 (4)	73 (3)	82 (3)
14	65	76	62	77

Production sites

Table 13 Noise Levels at Production Sites (117 Yards from source)

Site	**5 Second Leq dBA**	**5 Second Leq dBC**
15	59	74
16	51	69
17	41	58
18	42	61
19	41	58
20	46	63
21	55	65
22	44	64
23	41	62
Average	**47**	**64**

Octave Band Analysis

One-third octave band sound data were collected at each site using the Larson Davis SLM. The dominant sound frequencies at each oil and gas site were at or below 125 Hz. This is at the low end of the frequency spectrum, indicating that C-weighted sound levels may be more of a concern than A-weighted measurements. Octave band data are summarized in Table 14.

Table 14 Octave Band Dominant Frequencies

Site Type	**Dominant Frequency Level**
Drilling	63 Hz
Hydraulic fracturing	125 Hz
Completion	125 Hz
Production	16-31.5 Hz

Environmental Data

Environmental data for each site sampled are outlined in Table 15. The environmental data include temperature, relative humidity and wind speed. Measurements were not collected if temperatures were below 20°F or if wind speeds exceeded 10 mph. The temperature range for sites was 21°F to 76°F, the wind speed from 0.45 to 6.25 mph, and the humidity from 13% to 68%.

Table 15 Environmental Data

Site	Temperature (°F)	Relative Humidity (%)	Wind Speed (mph)
1	38	44	2.8
2	68	20	4.5
3	41	47	5.1
4	48	45	0.5
5	30	44	3.1
6	52	49	6.25
7	33	55	3.9
8	25	42	1.4
9	35	51	1.1
10	22	68	0.45
11	21	45	0.45
12	22	39	0.57
13	41	53	5.1
14	35	47	4
15	63	13	1.7
16	51	40	1.7
17	56	27	0.85
18	62	30	1.1
19	46	39	0.85
20	61	31	3.1
21	68	21	2.8
22	76	14	1.1
23	59	32	4.5

It is clear that the A- and C- weighted sound levels were reduced when sound walls were installed at drilling and fracturing sites. With the installation of sound walls, sound levels at drilling sites were reduced from 65 dBA to 59 dBA and 79 dBC to 73 dBC at 117 yards from the noise source. Sound levels at fracturing sites were reduced from 70 dBA to 59 dBA and 80 dBC to 74 dBC at 117 yards from the noise source. Even with the sound walls in place, the average C-weighted sound levels were measured at 74 dBC and 73 dBC for fracturing and drilling sites respectively at 117 yards from the noise source. These noise levels still exceed maximum permissible noise levels per COGCC Aesthetic and Noise Control Regulations. Figure 9 is a graphical representation of the difference in sound levels between drilling and fracturing sites with and without sound wall installations. The current COGCC permissible noise limit of 65 dBC is indicated by the red horizontal line. The current COGCC permissible noise limit of 55 dBA for residential zones during the daytime is indicated by the blue horizontal line.

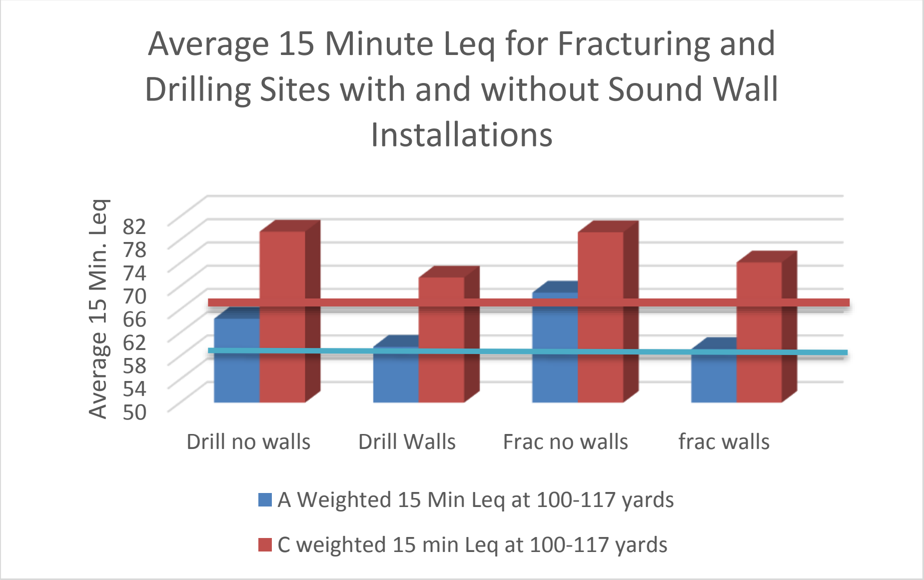
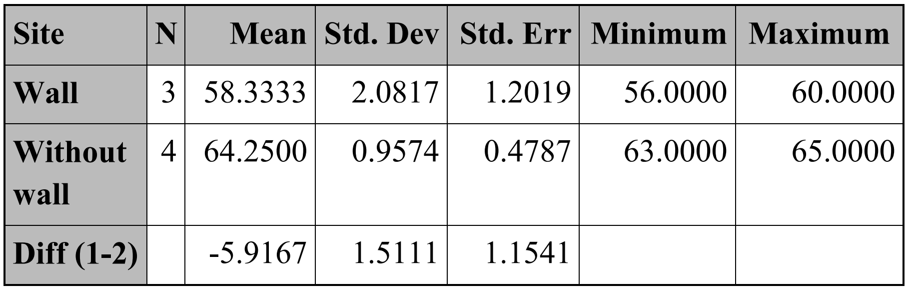


Figure 9 Sound Levels for Drilling and Hydraulic Fracturing Sites with and without Sound Walls

Statistical Analysis

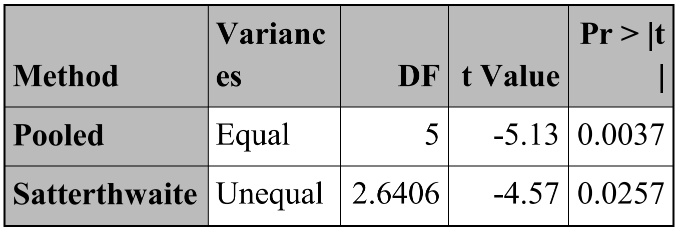
It is important to investigate if sound wall installations around oil and gas sites are equally effective in controlling high frequency noise as well as low frequency noise. Looking at the raw data, it is obvious that there is a reduction in noise when sound wall installations are in place. The researchers wanted to know if this was a statistically significant reduction or not. In order to evaluate if the difference in reduction between sound measurements collected at drilling sites with and without sound walls was statistically significant, a two-sample t-test was performed. Using the Statistical Analysis System (SAS) a two-sample t-test was conducted using A-weighted measurements at drill sites with and without walls. Comparatively, a two-sample t-test was also conducted using C-weighted measurements at drill sites with and without walls. The results of the t-tests were compared to one another to determine if there was a significant difference between A- and C- weighted measurements at drill sites with and without sound wall installations. A two-sample t-test was unable to be performed for fracturing sites due to the fact that only one fracturing site with sound wall installations was sampled. The researchers are aware that there is a limited sample size for drilling sites with and without sound wall installations. The variances for drill sites with and without walls were not equal for A- and C-weighted measurements. As a result, when conducting the statistical t-tests, the sattherthwaite P-value was used. The data for both A-weighted and C-weighted measurements were normally distributed. For this statistical analysis, the null hypothesis is that there is not a significant difference in reduction of noise measurements between drilling sites with and without sound wall installations. Or in other words, there is no significant difference between the mean SPL for drill sites with and without sound wall installations. An alpha level of 0.05 was chosen.

Based on the two-sample t-tests, there was a significant difference in reduction of A-weighted sound levels but not a significant difference in reduction of C- weighted sound levels between drilling sites with and without sound wall installations. The A-weighted two-sample t-test rejected the null hypothesis. Therefore, there is sufficient evidence to suggest that there is a significant difference in reduction of A-weighted sound measurements between sites with and without sound wall installations. The p-value for the A-weighted two-sample t-test was 0.0257 (p-value<0.05). The C-weighted two-sample t-test failed to reject the null hypothesis. This indicates that there is not sufficient evidence to suggest that there is a significant difference in reduction of C-weighted sound measurements between sites with and without sound wall installations. The p-value for the C-weighted two-sample t-test was 0.0694 (p-value >0.05). The SAS output is shown in Figures 10-13. Descriptive statistics for the A-weighted two-sample t-test are shown in Figures 10 and 11, while the descriptive statistics for the C-weighted two-sample t-test are shown in Figures 12 and 13.



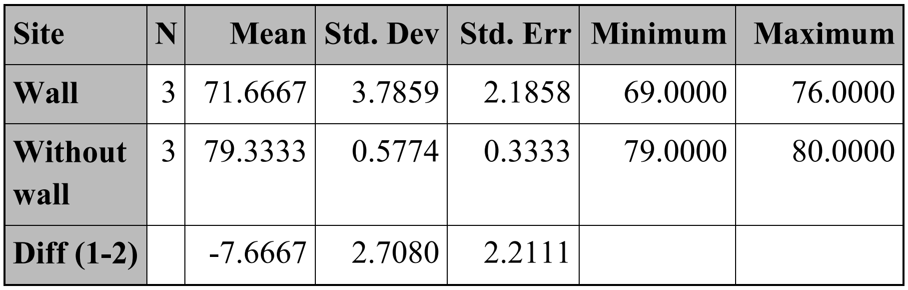
Site	N	Mean	Std. Dev	Std. Err	Minimum	Maximum
Wall	3	58.3333	2.0817	1.2019	56.0000	60.0000
Without wall	4	64.2500	0.9574	0.4787	63.0000	65.0000
Diff (1-2)		-5.9167	1.5111	1.1541		

Figure 10 Descriptive Statistics for A-weighted Data



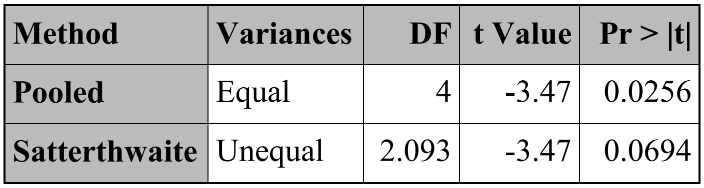
Method	Variances	DF	t Value	Pr > |t|
Pooled	Equal	5	-5.13	0.0037
Satterthwaite	Unequal	2.6406	-4.57	0.0257

Figure 11 P-Value for A-weighted Data



Site	N	Mean	Std. Dev	Std. Err	Minimum	Maximum
Wall	3	71.6667	3.7859	2.1858	69.0000	76.0000
Without wall	3	79.3333	0.5774	0.3333	79.0000	80.0000
Diff (1-2)		-7.6667	2.7080	2.2111		

Figure 12 Descriptive Statistics for C-weighted Data



Method	Variances	DF	t Value	Pr > |t|
Pooled	Equal	4	-3.47	0.0256
Satterthwaite	Unequal	2.093	-3.47	0.0694

Figure 13 P-value for C-weighted Data

As outlined in the methods section, sound measurements were collected at varying distances from the noise source at each type of oil and gas site. These measurements were used to model how sound levels decreased as distance from the noise source increased. Average sound levels at varying distances for each type of oil and gas site are modeled in Figures 14 and 15. It is clear that production sites had the lowest average sound levels in both the C- and A-weighted scale at every distance from the noise source. Hydraulic fracturing sites had the highest average sound level at every distance from the noise source. At 117 yards, all drilling, hydraulic fracturing and completion sites exceeded the COGCC maximum permissible sound level for residential and commercial zones in the A-weighted scale. The inverse square law for noise, as it relates to distance, is observed clearly in Figures 14 and 15. As distance is doubled, sound levels for each type of oil and gas site decreases by approximately 6 dB. The black horizontal lines represent the current COGCC limits of 65 dBC for C-weighted measurements and 55 dBA for the A-weighted permissible noise limit for residential zones.

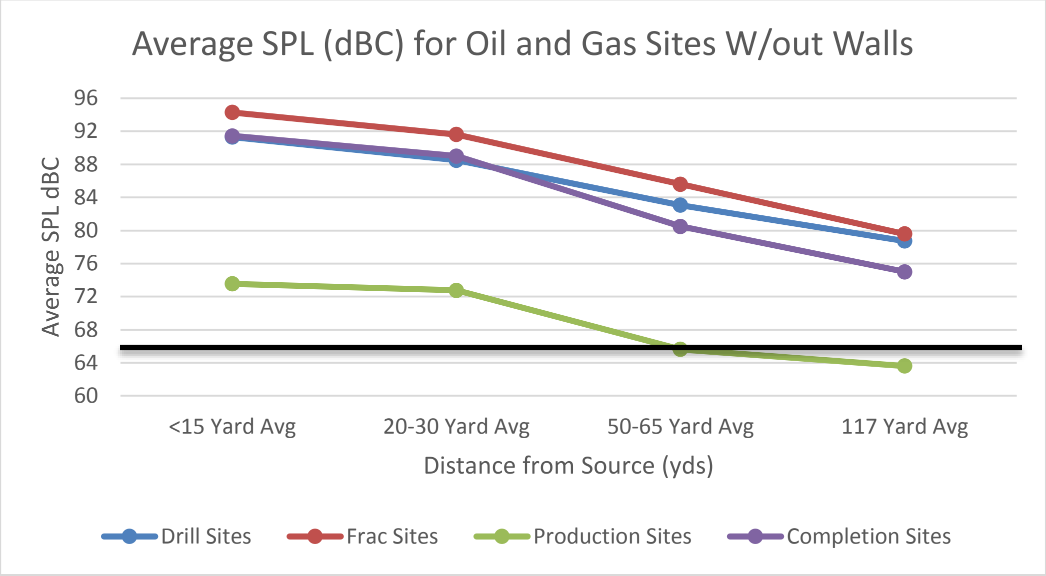


Figure 14 Average SPL (dBC) for Oil and Gas Sites without Walls

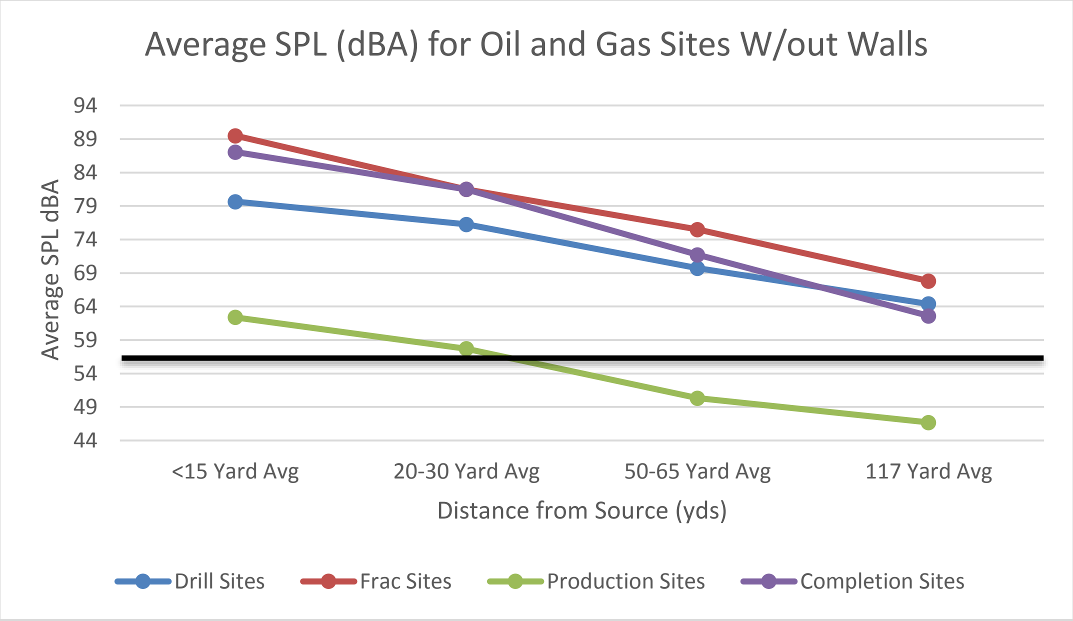


Figure 15 Average SPL (dBA) for Oil and Gas Sites without Walls

Attenuation Distance Charts

In addition to the sound measurements collected by Colorado State University researchers, researchers from the COGCC collected noise measurements from several oil and gas sites. The inverse square law for sound was used to estimate sound levels at a given distance, assuming a free field. These estimates were used to approximate the distance from the noise source needed to achieve a desired sound level in both the A-weighted and C-weighted scales. A longer distance is required to reach specified sound levels for C-weighted sound level measurements compared to A-weighted sound measurements due to the fact that the C-weighted measurements had higher sound pressure levels. The sound attenuation distances for A-weighted sound levels are illustrated in Table 16 while the sound attenuation distances for C-weighted sound levels are illustrated in Table 17.

Table 16 A- weighted Sound Attenuation Data Based on CSU and COGCC Measurements

	Site Type (Average 15-min L_{eq} at 117 yards (dBA)	**Desired SPL (dBA)**				
		65	60	55	50	
CSU Data	Drilling-no Walls (65)	350	622	1,106	1,968	**Estimated Distance to Achieve Desired SPL (Feet)**
	Drilling-with Walls (59)	175	312	554	986	
	Hydraulic fracturing-no Walls (70)	622	1,106	1,968	3,500	
	Hydraulic fracturing-with Walls (59)	175	312	554	986	
	Completion(62)	223	398	783	1393	
	Production	N/A (only obtained 5-second measurements)				
COGCC Data	**Site Type (Average 60-min L_{eq} at 117 yards (dBA) –No Walls**					
	Drilling Site 1	350	562	1,000	1,778	
	Drilling Site 2	124	211	375	668	
	Hydraulic fracturing Site 1	501	891	1,584	2,818	
	Hydraulic fracturing Site 2	354	630	1,122	1,995	

Table 17 C-weighted Sound Attenuation Data Based on CSU and COGCC Measurements

	Site Type (Average 15-min L_{eq} at 117 yards (dBC)	**Desired SPL (dBC)**				
		65	60	55	50	
CSU Data	Drilling-no Walls (79)	1,754	3,119	5,547	9,864	**Estimated Distance to Achieve Desired SPL (Feet)**
	Drilling-with Walls (73)	879	1,563	2,780	4,943	
	Hydraulic fracturing-no Walls (80)	1,968	3,500	6,223	11,067	
	Hydraulic fracturing-with Walls (74)	987	1,754	3,119	5,547	
	Completion (77)	1,259	2,239	3,981	7,079	
	Production	N/A (only obtained 5-second measurements)				
COGCC Data	**Site Type (Average 60-min L_{eq} at 117 yards (dBC)) –No Walls**					
	Drilling Site 1	1,585	2,818	5,012	8,912	
	Drilling Site 2	595	1,059	1,883	3,349	
	Hydraulic fracturing Site 1	1,585	2,818	5,012	8,912	
	Hydraulic fracturing Site 2	1,778	3,162	5,623	10,000	

Noise Contour Maps

Noise contour maps were developed using the Noise at Work Software to create a visual representation of noise contours at drilling and fracturing sites. Individual average sound level measurements collected using the SLM at various distances in each cardinal direction were used to create noise contour maps illustrating the average overall sound levels at a typical oil and gas site in each phase. Figures 16 through 23 are the noise contour maps with the average sound levels for typical drilling and fracturing sites with and without sound wall installations.

Noise Contours at Oil and Gas Sites

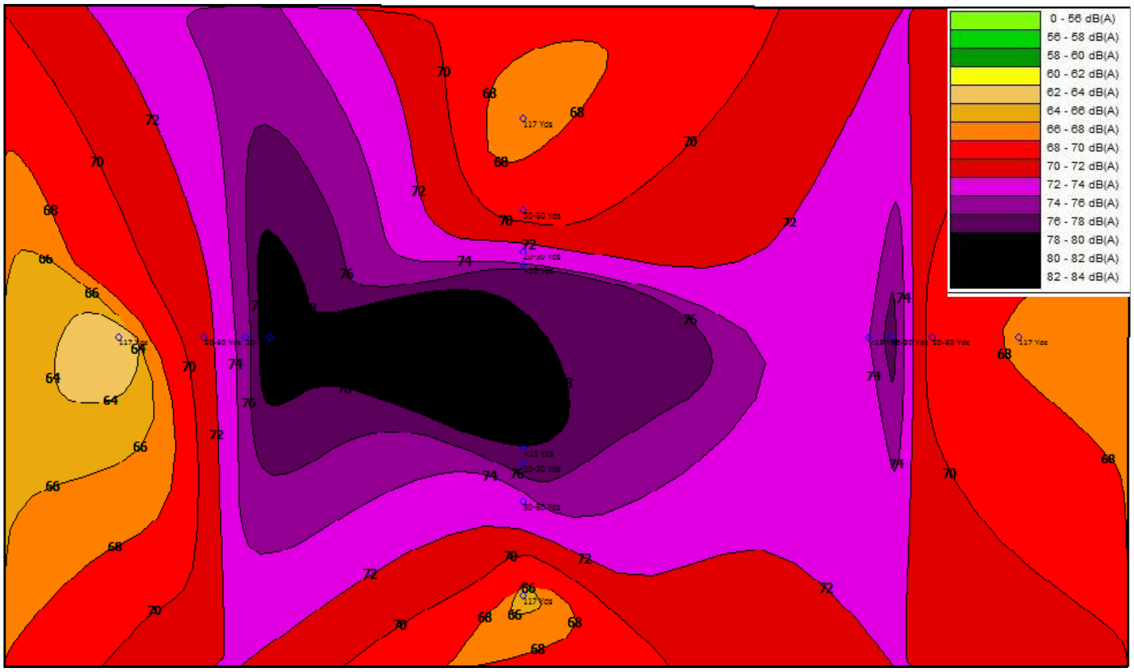


Figure 16 Average Drilling Site without Sound Wall Installation (dBA)

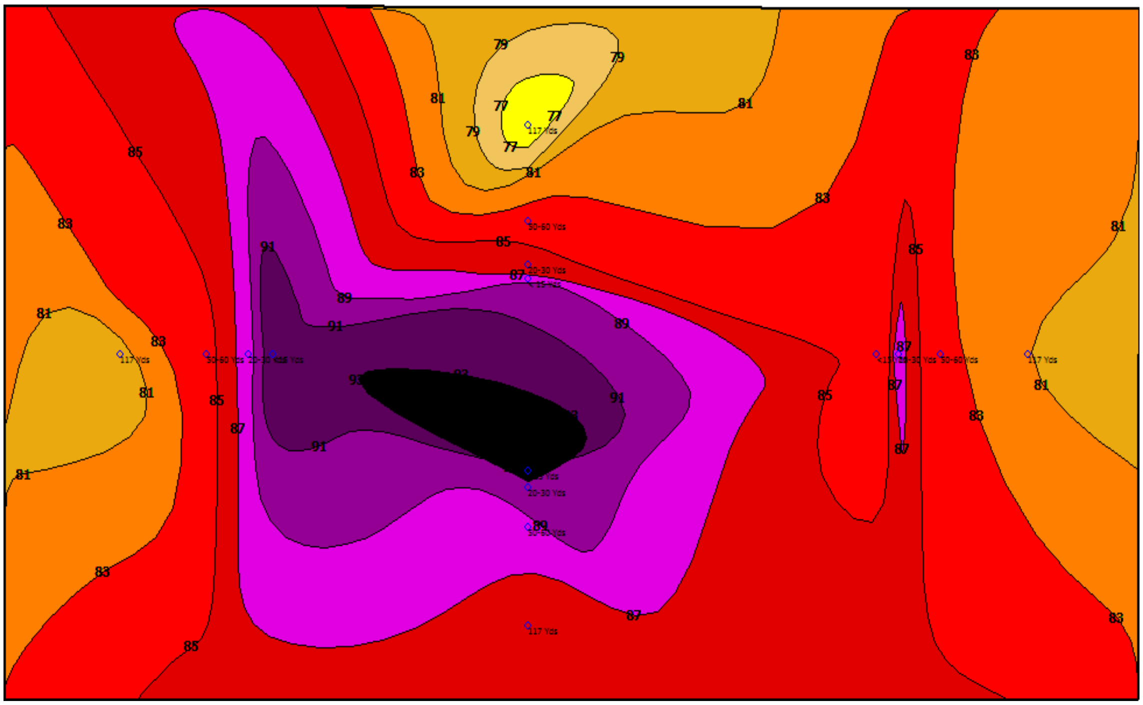


Figure 19 Average Drilling Site without Sound Wall Installation

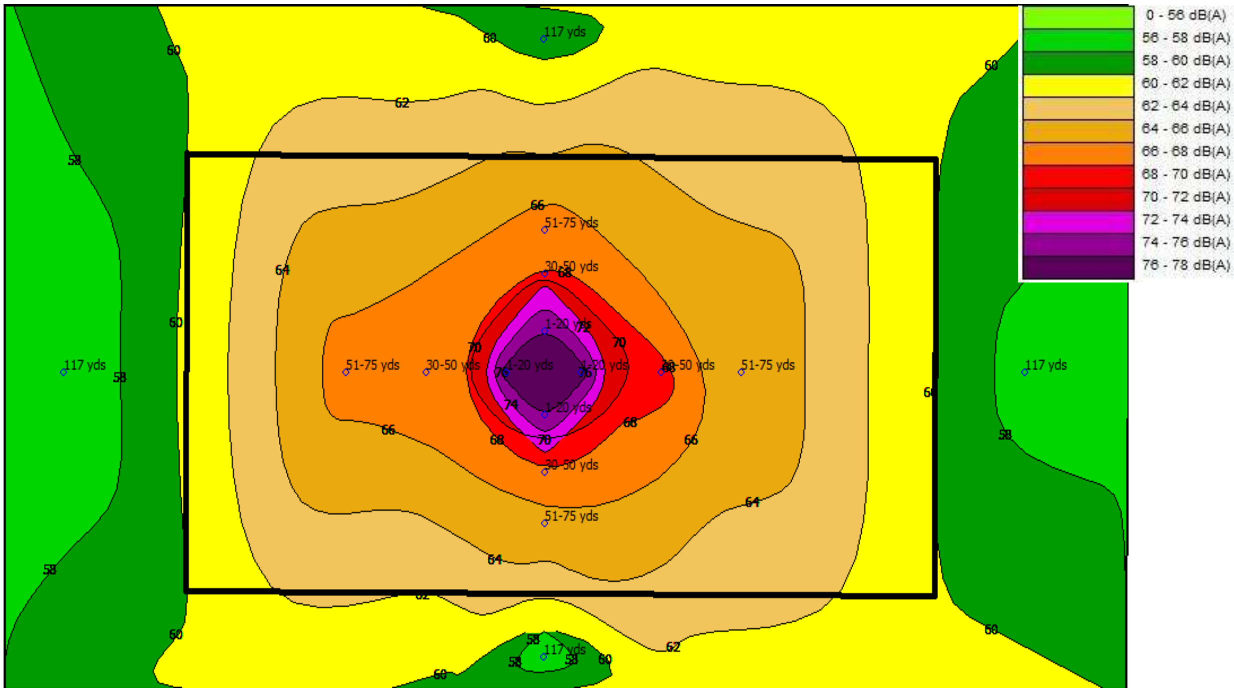


Figure 22 Average Drilling Site with Sound Wall Installation (dBA)

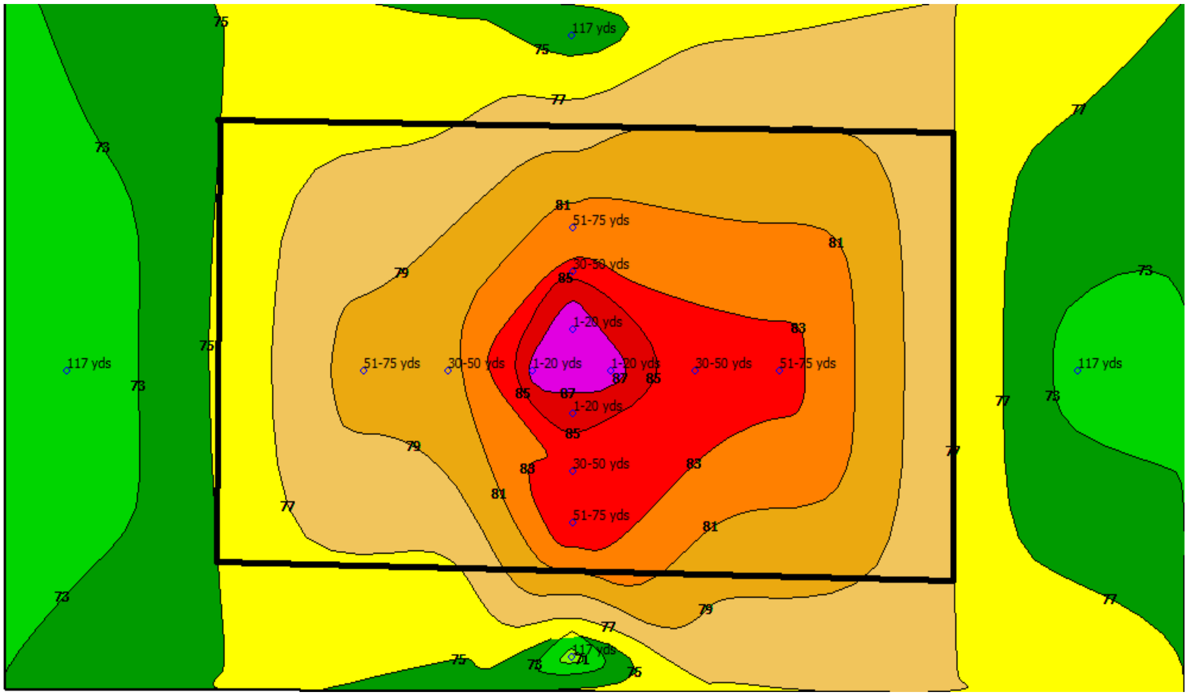


Figure 25 Average Drilling Site with Sound Wall Installation

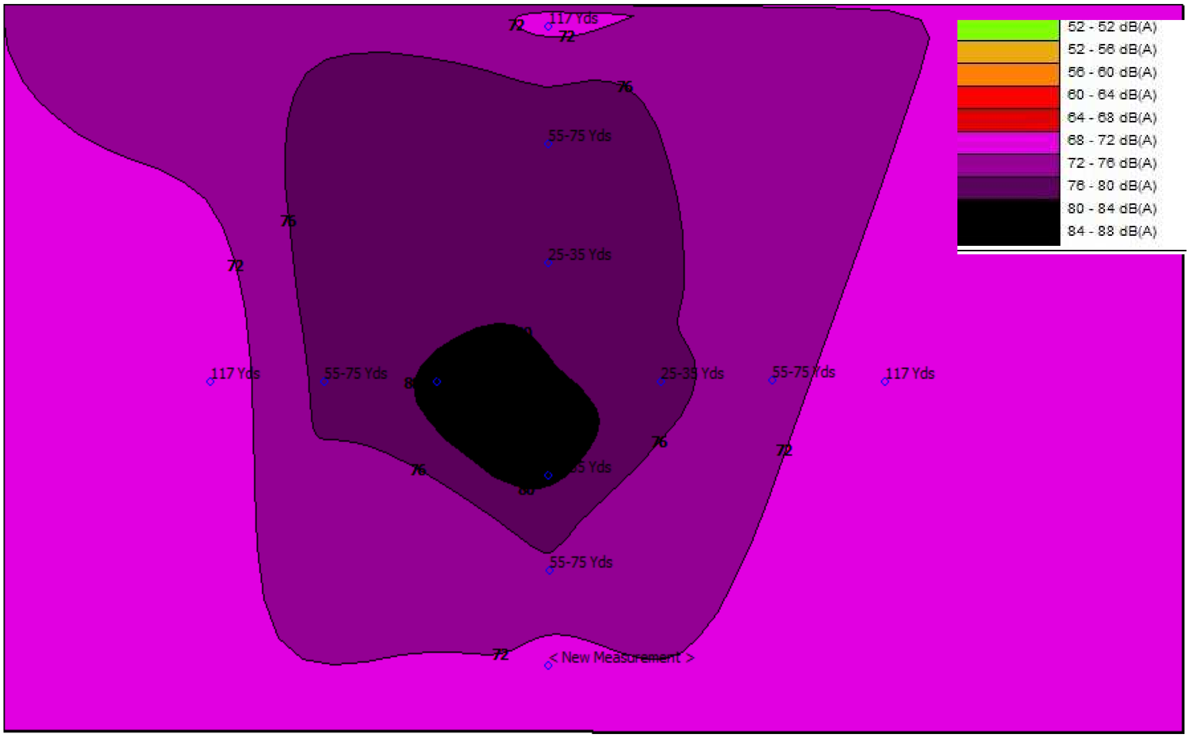


Figure 28 Average Fracturing Site without Wall Installation (dBA)

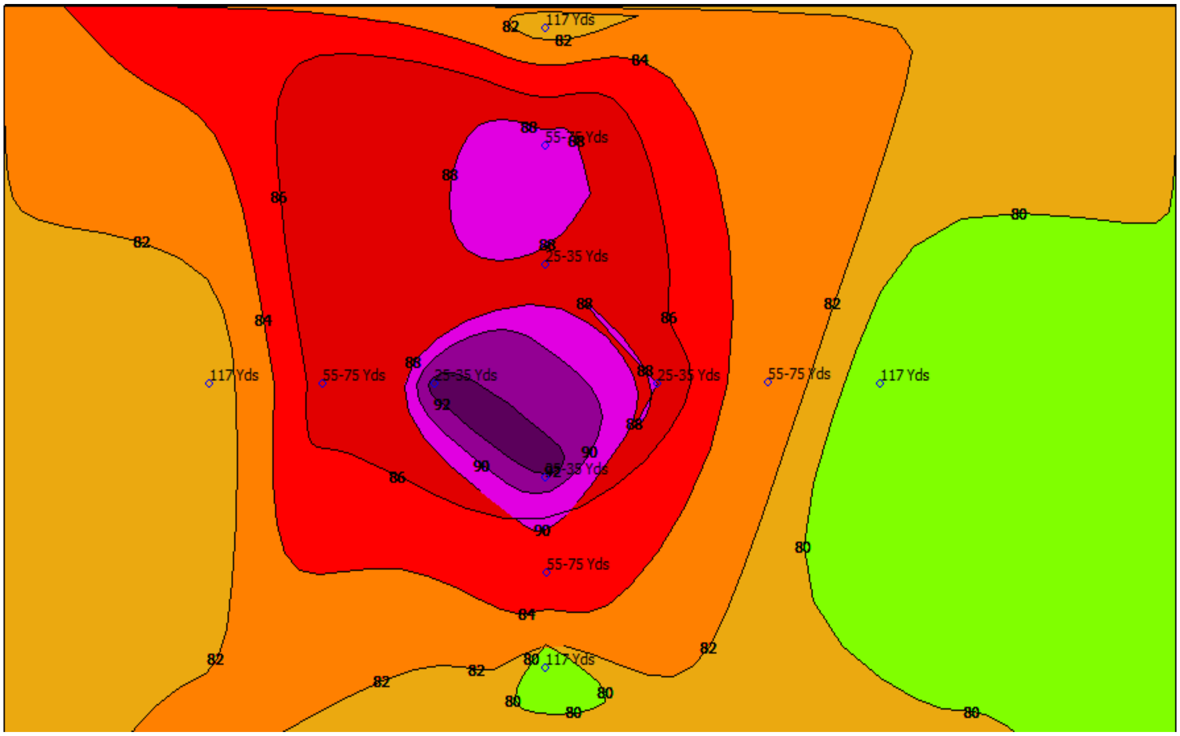


Figure 31 Average Fracturing Site without Sound Wall Installation (dBC)

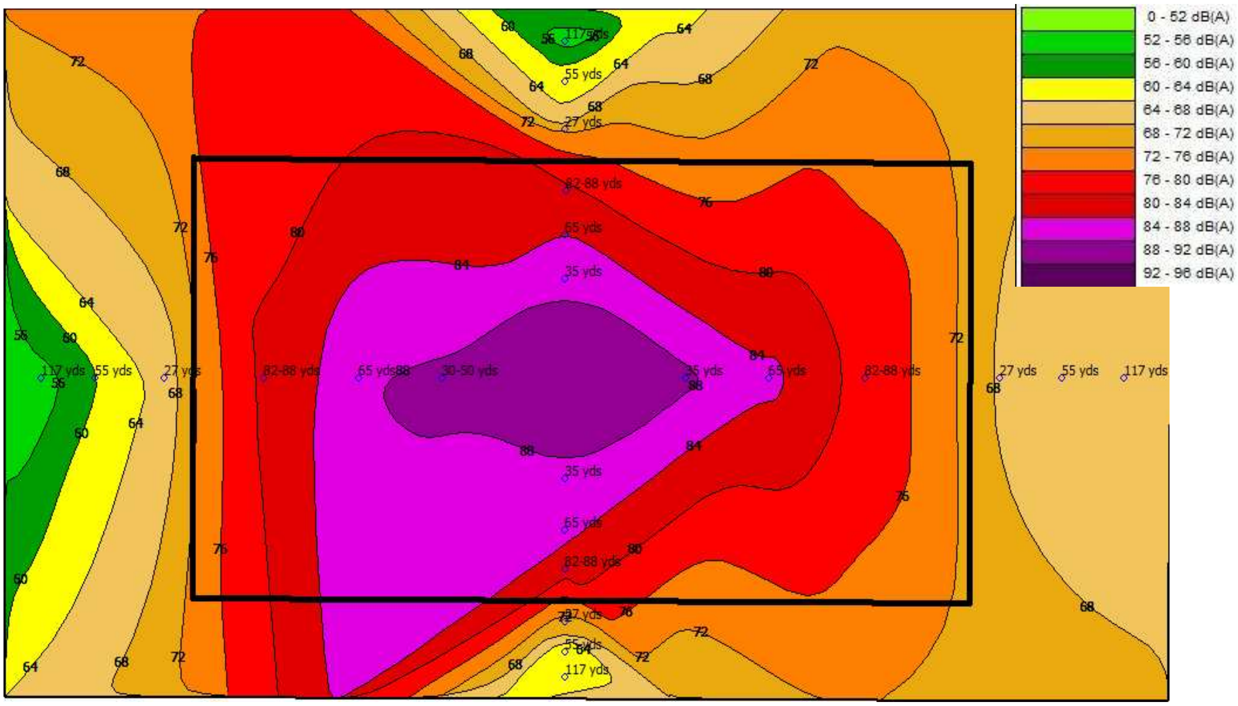


Figure 34 Average Fracturing Site with Sound Wall Installation (dBA)

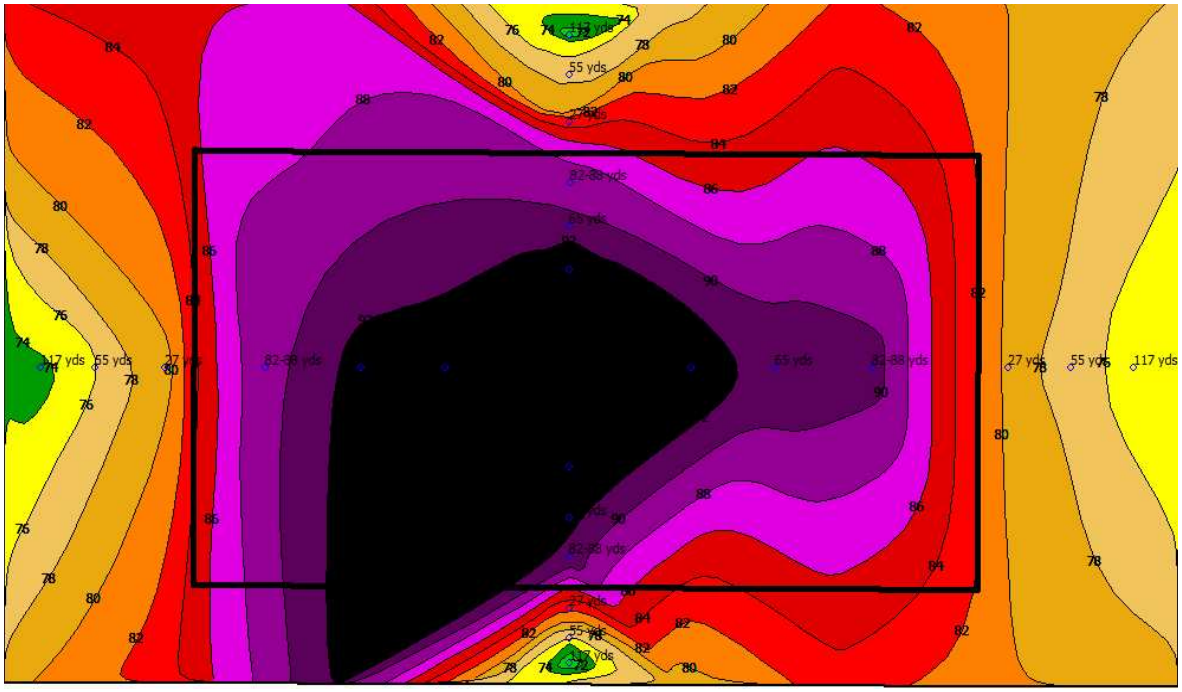


Figure 36 Average Fracturing Site with Sound Wall Installation (dBC)

GPS coordinates were recorded where each sound measurement was collected at oil and gas sites in order to use Google Earth® in conjunction with the Noise at Work Software to create detailed noise maps overlapping with individual sites. This technique allowed the researchers to provide the COGCC and operators a way of visualizing the noise contours at specific sites. This information can be used to identify areas of concern regarding noise at different types of oil and gas sites and it can be used to see how the sound travels beyond the confines of the site itself. Figure 24 is an example of the Noise at Work Software used with Google Earth® .

Figure 39 Noise Contour Map using Google Earth®

CHAPTER 6: DISCUSSION

There is a difference in sound levels between the different phases of oil and gas development. It is evident after referring to Figures 14 and 15 that hydraulic fracturing sites had the highest sound levels while sites in the production phase had the lowest sound levels. Hydraulic fracturing sites appear to have the highest sound levels at the noise source however, as the distance from the noise source increases, the average sound levels for hydraulic fracturing sites become very similar to the average sound levels of drill sites. Considering the accuracy of the sound instruments being +/- 1 or 2 dB, it is difficult to conclude that hydraulic fracturing sites are significantly louder than drilling sites at 117 yards on average. Four of four (100%) of the A-weighted, 15-minute L_{eqs} at 117 yards for drilling sites without sound wall installations exceeded the current COGCC regulations for residential and commercial zones. Three of three (100%) of the A-weighted, 15-minute L_{eqs} at 117 yards for drilling sites with sound wall installations exceeded the current COGCC regulations for residential zones. No A-weighted 15-minute L_{eq} at 117 yards for drilling sites with or without sound wall installations exceeded the current COGCC limit for light industrial or industrial zones. Two of four (50%) of the A-weighted 15-minute L_{eqs} at 117 yards for hydraulic fracturing sites without walls exceeded the current COGCC limit for light industrial zones, while four of four (100%) of the A-weighted L_{eqs} for the same hydraulic fracturing sites exceeded the limits for residential and commercial zones. The hydraulic fracturing site with sound wall installations had an A-weighted 15-minute L_{eq} that exceeded the current COGCC limit for residential zones but not commercial zones.

The C-weighted sound level measurements were significantly higher than the A-weighted sound measurements at every oil and gas site. This indicates a low frequency noise issue at oil and gas sites, which was confirmed with the octave band analysis. The dominant frequency at every oil and gas site was in the low frequency range, with the highest dominant frequency at 125 Hz at hydraulic fracturing and completion sites. While sound levels were decreased when sound wall installations were present, the C-weighted sound level measurements with walls continued to exceed 65 dBC. Using the two-sample t-test for drilling sites with and without walls, there was a significant difference in A-weighted sound levels but not for C-weighted sound levels at 117 yards. This affirms the fact that lower frequency noise is more difficult to control than higher frequency noise. The Fresnel equation and how it relates frequency explains why there is a greater difference in sound reduction using sound wall installations for A-weighted sound levels than C-weighted sound levels.

In addition to selecting sites that had little to no background noise, it was important to collect environmental measurements including temperature, relative humidity, and wind speed at each site. Although the SLM and noise dosimeters were equipped with wind screens, sound measurements were not collected if wind speeds exceeded 10 mph. Environmental parameters were kept within a certain range in an effort to standardize measurements that were collected at different sites. In addition to maintaining a certain level of standardization, measurements were not recorded in extreme temperatures due to the sound equipment manufacturer's recommendations. The operating temperature range for the Larson Davis dosimeters and SLM/OBA is between 14°F and 122°F. Permanent damage to the instrument can occur if the temperature exceeds 140°F or dips below -4°F.(30)

The COGCC and oil and gas operators can use the sound attenuation data outlined in Tables 16 and 17 as an initial estimate of the distances that occupied building units can be affected by excess noise levels in both the A- and C-weighted scale. For each type of site, excluding production sites, the average noise level at 117 yards was used in the inverse square law equation to calculate the approximate sound level at a given distance from the noise source. It is evident that greater distances away from the noise source are needed in order to achieve lower sound levels in the C-weighted scale than in the A-weighted scale. Greater distances are needed for C-weighted sound levels due to the fact that on average, the C-weighted sound levels were much higher than the A-weighted levels.

The noise contour maps are effective tools when evaluating the noise “footprint” of an oil and gas site. The maps can be used to identify the loudest areas of a particular site as well as analyze how the sound travels farther away from the noise source. The noise map software can be used in conjunction aerial photographs of oil and gas sites to identify specific equipment and areas that produce the most noise on a site. These data can be used to develop site-specific controls to reduce noise. For example, rig orientation can be evaluated using noise contour maps. If certain areas of a site produce more noise than others, the rig can be re-oriented in such a way that the majority of the noise is emitted in a more desirable direction away from communities or businesses.

A very limited amount of research has been conducted regarding environmental noise and the oil and gas industry, making this an interesting but challenging area of research. Previous studies that investigated environmental noise resulting from oil and gas operations used different methodology to obtain sound measurements. Some studies collected measurements at different distances from the noise source while other studies measured completely different types of sites and equipment. This makes it difficult to compare the results of those studies to one another. Out of the three studies discussed previously in the relevant studies section, only the recent COGCC study addressed C-weighted sound levels. The La Plata County study researchers collected measurements from a variety of different noise sources ranging from individual pumps and compressors to overall construction noise at an oil and gas site. It was not stated if these sites had sound wall installations in place or not. It can be concluded from the La Plata County study that at 500 feet from the various noise sources the average sound level was 66 dBA. An average sound level of 66 dBA at 500 feet is higher than the levels observed by the Colorado State University researchers. It is important to note that the La Plata County study was conducted in 1998 where much of the equipment may have been louder and less engineering controls to control noise may have been in place. In addition to the La Plata County study, the Fort Worth study didn't address C-weighted noise levels. It was shown by the Fort Worth study that when 12-foot sound walls were installed on an average drill site, sound levels decreased from 72-77 dBA to 64-68 dBA at a distance of 200 feet from the source. The Colorado State University researchers observed a similar decrease in A-weighted noise when 32-foot sound walls were installed on an average drill site. According to the Colorado State University research, on average the installation of sound walls on drilling sites decreased the A-weighted 15-minute L_{eqs} from 65 dBA to 59 dBA.

Unlike the La Plata and Fort Worth Studies, the COGCC study, conducted in 2015, addressed both A-weighted and C-weighted noise levels. Unlike the other two studies, the COGCC study followed similar protocol as the Colorado State University study. Measurements were collected at 117 yards from the noise source at drilling and hydraulic fracturing sites with and without sound wall installations. The only difference in protocol was that the COGCC conducted measurements over a 24-hour period compared to the Colorado State University researchers conducting measurements over a 15-minute period. On average, the COGCC results were within 2 dB of the Colorado State University results. The largest discrepancy was between the A-weighted sound levels for drilling sites with sound wall installations. The COGCC reported an average 24-hour sound level of 54 dBA for drilling sites with sound walls while Colorado State University reported an average 15-minute sound level of 59 dBA for drilling sites with sound walls. The COGCC reported similar decreases in sound levels between sites with and without sound wall installations. It can be concluded that the COGCC 24-hour sound level results support Colorado State University's 15-minute sound level measurements for drilling and fracturing sites. The Colorado State University's 15-minute sound level measurements may be used as an estimator of 24-hour noise levels. The similarities between the 24-hour COGCC results and the 15-minute Colorado State University results indicate that noise at oil and gas operations are in a relatively steady state. Once a site is operational, there is not much variation in the noise that is produced.

Study Limitations

A very limited number of oil and gas sites appeared on Google Earth® to create the noise contour maps. Perhaps for future evaluations using the noise contour software, aerial images obtained by oil and gas operators of each specific site can be used instead. This way, a noise contour map can be created on top of a layered image of each oil and gas site, not just the sites that appear on Google Earth®. Another limitation involved the fact that the noise levels at production sites were relatively quiet. The gain setting was outside of the dynamic range for the dosimeters to measure 15-minute L_{eq} measurements at productions sites. The gain setting for the dosimeters was set to a level where low levels of noise were not recorded. Instead of using the dosimeters, 5-second L_{eq} measurements were collected at production sites using the SLM/OBA.

Additionally, the inverse square law for noise was used to predict noise attenuation over certain distances. The inverse square law assumes the attenuation of noise in a free field. In reality, the noise most likely did not travel in a free field. There may have been some attenuation of noise due to topography and other factors.

Noise measurements were collected during five-second and 15-minute intervals. Even though sampling while oil and gas operations were running as loud as possible allowed the researchers to obtain a “worst-case” scenario, variability in sound levels throughout the day or night could not be determined. Without a 24-hour sampling frame, community noise parameters such as L_{90} values and the community noise equivalent level (CNEL) could not be calculated. In addition to having “worst-case” scenario sound measurements over a 15-minute time period, it would be useful to measure the average sound level over a 24-hour period. With the limited number of active oil and gas sites in the Northern Colorado area that were acceptable to sample, the researchers were able to sample twenty-three sites in total during the study time frame. Ideally, to evaluate consistency, a greater number of fracturing sites with walls and completion sites should be sampled. It would also be valuable to sample oil and gas sites in different parts of Colorado with diverse topography during different times of the year to investigate any variations in noise levels.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

This research can be used as a reference when evaluating noise produced by different types of oil and gas sites. In addition to providing the COGGC with useful data to evaluate the effectiveness of the current COGCC noise regulations, the noise evaluations of oil and gas sites conducted in this study addressed the following questions:

1. Is there a significant difference in noise levels between the four phases of oil and gas operations?

Each phase of oil and gas operations had different average noise levels at 117 yards from the noise source. The highest sound level measurements in the A- and C-weighted scales, on average, were collected at hydraulic fracturing sites. At a distance of 117 yards from the noise source, drilling and hydraulic fracturing sites had similar noise measurements. The most significant difference between drilling and hydraulic fracturing sites was a 5 dBA lower A-weighted average 15-minute L_{eq} at drilling sites without walls than hydraulic fracturing sites without walls 117 yards from the noise source. Drilling and hydraulic fracturing sites were within one dBC of each other with and without sound walls at a distance of 117 yards from the noise source. The average A-weighted sound level measurements collected at production sites were at least 15 dBA lower than the A –weighted 15-minute L_{eq} measurements collected at all drilling, hydraulic fracturing and completion sites. The average C-weighted sound level measurements collected at production sites were at least 8 dBC lower than the C-weighted 15-minute L_{eq} measurements collected at all drilling, hydraulic fracturing and completion sites.

2. Are current mitigation practices sufficient to provide community protection from excess sound levels?

Oil and Gas Sites with sound wall installations had lower sound levels in both the A- and C-weighted scales than those without sound wall installations. However, this reduction in noise was not sufficient enough to categorize drilling and hydraulic fracturing sites as “in compliance” with the current COGCC noise regulations. On average, production sites without mitigation do not exceed current COGCC noise regulations. It is recommended that additional measures are taken to further reduce sound levels at drilling and hydraulic fracturing sites. It is essential to control low frequency noise present in the C-weighted measurements. If the C-weighted noise is controlled, the A-weighted noise will be reduced as well.

3. Do the sound levels exceed current COGCC limits?

Regarding A-weighted sound level measurements, the comparison between measured sound levels and current COGCC limits is illustrated in Table 7. It is important to highlight that every drilling and hydraulic fracturing site with and without sound walls had average noise measurements at 117 yards that exceeded the current COGCC residential daytime and nighttime limits. Every drilling and hydraulic fracturing site without sound walls exceeded the current COGCC commercial daytime and nighttime limits. Seventy-five percent of drilling sites without walls and 100% of hydraulic fracturing sites without walls exceeded the current COGCC light industrial nighttime limits. A significantly lower proportion of production sites exceeded the COGCC limits for A-weighted sound levels. Regarding C-weighted sound level measurements, every drilling, hydraulic fracturing and completion site exceeded the current COGCC limit of 65 dBC. The average C-weighted sound level at production sites was 64 dBC. A slight increase of 1 dB places the average production site at the current COGCC limit of 65 dBC. Considering the accuracy of the type one and type two sound measuring devices that were used, it can't be concluded that the average production site is below the current COGCC limit of 65 dBC.

Recommendations

There are a plethora of sources on an oil and gas site that contribute to noise. While oil and gas operators commonly use different mitigation techniques, oftentimes those techniques aren't enough to significantly decrease the noise level. There are several possible mitigation techniques that may be used in addition to installing sound walls to further abate the noise at oil and gas sites to help achieve the permissible noise levels. Several techniques aside from sound wall installations are listed below. This list is not a comprehensive list of all possible mitigation techniques that can be used to reduce sound levels at oil and gas sites.

- Motor vehicles used to access well sites generate noise. Remote automated monitoring systems can be used to eliminate the need for heavy truck traffic to well sites.
- Sound barriers constructed from steel and sound-absorbing material can be used to mitigate noise generated from engines. L-shaped sound barriers can be installed around engines to mitigate engine noise.
- Sound-insulating buildings may be constructed around permanent noise producing structures such as compressors and pump-jacks.
- Installing mufflers on engines and compressors may help to minimize the noise impact of an oil and gas site.

- Rig orientation may be a key control method. "Pointing" the noise sources away from residential areas may reduce the noise propagated toward the residential areas (e.g., pointing the exhaust side of machinery away from the receiver).

- Portable acoustical panels around individual equipment, in conjunction with temporary perimeter sound walls, can be used.
- Rig floor sound blanket panels can be installed to control the noise near the source.
- The use of electric rigs and equipment may reduce sound levels. However, additional research and noise measurements need to be collected to assess the effectiveness of electric rigs in terms of reducing sound levels.

It is recommended that the oil and gas industry continue to collaborate with private and government entities to work toward reducing sound levels produced by oil and gas operations, specifically drilling and hydraulic fracturing operations.

Future Research

There has been little research on evaluating and characterizing environmental noise produced by oil and gas operations. With the oil and gas industry expanding throughout the United States, it is important to continue to evaluate the community and environmental impacts of noise resulting from these sites. This study has opened the door for additional researchers to evaluate and further understand environmental noise in the oil and gas industry. Further research to control low frequency noise produced by oil and gas operations is essential. Also, there is a need for additional sound surveys to be conducted encompassing a larger sample size of oil and gas sites. In future studies it would be beneficial to collect sound measurements over a longer period of time to understand how noise may fluctuate between day-time and night-time levels.

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