DISSERTATION

OCCUPATIONAL NOISE EXPOSURE AND HEARING ASSESSMENT OF HYDRAULIC FRACTURING WORKERS: QUIET VERSUS CONVENTIONAL FLEETS

Submitted by

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ABSTRACT

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Oil and gas extraction companies are exempt from implementing hearing conservation programs for their workers according to the Occupational Safety and Health Administration's (OSHA) noise standard. The occupational noise exposure and hearing status of these workers has not been published in scientific literature before the present study, presumably due to this exemption. In this study, area and personal noise exposures and worker hearing acuity were measured at both conventional and quiet hydraulic fracturing fleets, allowing a comparison between the fleets. Quiet fleets refer to the use of engineering controls to decrease noise levels of the pumps while conventional fleets do not employ these measures. In both fleets, the authors conducted personal noise dosimetry, equipment noise measurements, and pure tone audiometry pre- and post-work shift to determine if there were temporary threshold shifts (TTS) in hearing. Based on the personal noise dosimetry results, 42/50 (84%) of the quiet fleet and 34/34 (100%) of the conventional fleet workers sampled were at or over 100% noise dose according to the American Conference of Governmental Industrial Hygienists' (ACGIH) noise Threshold Limit Value (TLV). Based on the OSHA Permissible Exposure Limit (PEL) noise criteria, 9/50 (18%) of the quiet fleet workers and 15/34 (44.1%) of the conventional fleet workers were at or over 100% noise dose. Workers in both fleets experienced TTS, but no significant difference was observed between the types of fleets in relation to TTS. Most equipment of both fleets exceeded 85 decibels, but the pumps of the quiet fleet were ~14 dB lower than those of the conventional fleet. Although the quiet fleet noise controls reduced personal noise exposure, a portion of the quiet fleet workers sampled still faced noise levels that could increase the risk of hearing loss. The researchers suggest the initiation of a hearing conservation program despite OSHA exemption to safeguard worker health and recommend workers involved in certain job tasks employ dual hearing protection based on the exposure monitoring results.

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Thank you, Dr. B., for all your support these past two years. I can never thank you enough for your patience and understanding and your never-ending belief in me, even when I no longer believed in myself. Under your supervision and weekly meetings, I have grown as a researcher, a professional industrial hygienist, and person.

To my committee members, Dr. Candace Tsai, Dr. Michael Van Dyke, Dr. Daniel Autenrieth, and Professor Tiffany Lipsey: Thank you for helping me to grow as a researcher and scientist and for your continued support and feedback. I also want to thank Dr. Ann Hess for statistical analysis support during this project.

I want to thank the operator, subcontractor, and volunteer hydraulic fracturing workers for their significant support of this project, without which this study would not have been possible. I would also like to thank the Colorado State University OSHA lab for the use of their equipment. I appreciate NIOSH for supporting my studies and research through Grant Number T42OH009229 from CDC NIOSH Mountain and Plains Education and Research Center.

Thank you to the workers at Ram Kidz located in the Colorado State University library. My husband, son, and I spent nearly every Saturday and Sunday at the library because of the child watch services provided by Ram Kidz. My son loved it, and I was able to focus on my studies and my dissertation.

Thank you to my parents, Steve and Sandra Manning, that have always believed in me and supported my dreams, including this doctoral journey. Biggest thanks to my husband Chris and my son Bo for their support and patience during this endeavor.

DEDICATION

To my husband Chris and my son Bo.

To Chris: Thank you for believing in me and supporting my dreams. Without you, I would not have accomplished so much.

To Bo: Thank you for being my light.

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LIST OF ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
AL	Action Level
ANSI	American National Standards Institute
AAO	American Academy of Otolaryngology
ASHA	American Speech-Language-Hearing Association
CAOHC	Council for Accreditation in Occupational Hearing Conservation
CDC	Centers for Disease Control and Prevention
CSU	Colorado State University
dB	Decibel
dBA	Decibel in A-weighted scale
dBC	Decibel in C-weighted scale
HCP	Hearing Conservation Program
HPD	Hearing Protection Device
Hz	Hertz
MPANL	Maximum Permissible Ambient Noise Levels
NIHL	Noise Induced Hearing Loss
NIOSH	National Institute for Occupational Safety and Health
NORA	National Occupational Research Agenda
NRR	Noise Reduction Rating
OBA	Octave Band Analysis
OGE	Oil and Gas Extraction
OHC	Certified Occupational Hearing Conservationist

OSHA	Occupational Safety and Health Administration
OR	Odds Ratio
PEL	Permissible Exposure Limit
PTS	Permanent Threshold Shift
SLM	Sound Level Meter
SPL	Sound Pressure Level
STS	Standard Threshold Shift
TTS	Temporary Threshold Shift
TLV	Threshold Limit Value
TWA	Time-Weighted Average

CHAPTER 1: INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) estimates that 22 million workers in the United States (US) are exposed to hazardous levels of noise and that these exposures can lead to permanent noise-induced hearing loss (NIHL) (Tak et al., 2009). Further, there is concern that workers in the oil and gas extraction (OGE) sector are at increased risk of NIHL, but alarmingly, OGE development companies are exempted from parts (c)-(n) of the Occupational Safety and Health Administration's (OSHA) Occupational Noise Exposure Standard—the same standard that mandates employees be protected from hazardous noise. Assumably, due to this partial noise-standard exemption, there is limited information available regarding occupational noise exposure and hearing loss in the OGE industry. There are no known peer-reviewed studies on hearing loss or noise exposure in the OGE extraction sector in the US, and these workers are likely to suffer from work-related hearing loss (Lawson et al., 2019).

OSHA's Occupational Noise Exposure Standard (OSHA, 29 CFR 1910.95) requires general industry employers to protect worker hearing by limiting employee noise exposure to an 8-hour time-weighted average (TWA) of 90 decibels (dBA) as the permissible exposure limit (PEL) and to an 8-hour TWA of 85 dBA (or 50% dose) as the action level (AL) for implementing a hearing conservation program (HCP). Because OGE employers are partially exempt from OSHA's noise standard, these employers are not required to implement HCPs, perform noise monitoring, or administer audiometric hearing tests. Given this partial exemption, the occupational health community suspects, but does not have the requisite data, to determine if OGE workers are exposed to hazardous levels of noise and if they are suffering from work-related NIHL. Assessment of OGE worker noise exposures and hearing acuity is critical to determine if noise mitigation is required to protect worker hearing in the OGE sector.

Occupational noise exposure is a common workplace hazard. NIHL can result from hazardous noise exposure and is a form of sensorineural hearing loss, which is a form of hearing loss that is permanent. Repeated exposure to noise can lead to the degradation of stereocilia and auditory nerve cells. In addition to hearing loss, overexposure to noise is associated with hypertension, high cholesterol, hearing difficulty, tinnitus, and safety risk due to reduced communication ability among workers(Kerns et al., 2018). The burden of occupational noise exposure has impacts beyond the worker level and can cause substantial societal health and financial burdens. The associated annual occupational NIHL-compensation costs in the US alone are estimated to be more than $242 million and growing (Basner et al., 2014; Vos et al., 2012). To alleviate this burden, it is imperative to identify workplace hazardous noise exposures and worker temporary hearing loss, or repeated temporary threshold shifts (TTS), to prevent permanent or irreversible hearing loss (Dobie & Kopke, 2020).

In 2022, there were an estimated 218,966 OGE workers employed in the US, and that number is expected to increase by 7,578 by 2027 (Ross, 2022). In Canada, a bulletin published by WorkSafe BC writes that a majority of OGE drilling employees are exposed to hazardous levels of noise, (WorkSafeBC, n.d.-b) and 45% of these workers showed signs of suffering from NIHL (WorkSafeBC, n.d.-a). In the US, NIOSH and the National Occupational Research Agenda (NORA) Oil and Gas Extraction Council identified noise surveillance and characterization as a critical need in the OGE industry (NIOSH, n.d.; NORA Oil and Gas Extraction Sector Council, 2018). This study addresses, in part, NORA's request to evaluate noise exposure and hearing loss in the OGE industry by focusing on one phase of the OGE development process: hydraulic fracturing.

Hydraulic fracturing, or fracking, is the process of injecting water, chemicals, and sand into the ground to fracture shale rock and extract petroleum (King, 2010). Researchers in the current study investigated the noise exposure from two forms of fracking: conventional and quiet fleet. Conventional fracking is hydraulic fracturing without the use of engineered noise controls for the fracking pumps and engines that power the pumps, while quiet fleet fracking uses engineering controls to reduce sound emissions by insulating the fracking pumps and engines that power the pumps. The authors compared quiet fleet and conventional fracking data to determine if these engineering controls were effective for reducing worker exposure to noise.

The specific aims (SA) of this study were to (1) Determine personal noise exposures for oil and gas employees, (2) Characterize noise emissions from oil and gas operations and equipment, and (3) Determine if oil and gas employees suffer from temporary threshold shifts in hearing.

<u>Specific Aim 1 – Determine personal noise exposures for oil and gas employees.</u>

Alternative Hypothesis (HA) 1: Hydraulic fracturing employees are exposed to worksite noise exceeding published occupational exposure limits.

Null Hypothesis (H0) 1: Hydraulic fracturing employees are not exposed to worksite noise exceeding published occupational exposure limits.

HA 2: Conventional fracturing employees' personal noise exposures are significantly greater than quiet fracturing employees' personal noise exposures.

H0 2: There is no significant difference between quiet and conventional fracturing employees' personal noise exposures.

The SA1 hypotheses on noise exposure limits were addressed by performing personal noise dosimetry on OGE workers who perform hydraulic fracturing job tasks at quiet fleet and conventional fleet sites. The noise dosimeters were set to measure for compliance (8-hour duration, slow response) with the OSHA action level (AL) (90 dBA criterion, 80 dBA threshold, 5 dB exchange rate), OSHA PEL (90 dBA criterion, 90 dBA threshold, 5 dB exchange rate), and the American Conference of Governmental Industrial Hygienists Threshold Limit Value (ACGIH TLV) (85 dBA criterion, 80 dBA threshold, 3 dB exchange rate). Personal noise exposure samples were compared to the OSHA PEL, the OSHA AL, and the ACGIH TLV to determine whether employees were overexposed to noise or if they would benefit from being enrolled in an HCP. The means and standard deviations for the dosimetry results were segregated by job tasks and reported as average noise exposures for fracturing processes. These data were analyzed with summary statistics for the proportion of workers that exceeded these thresholds presented in Tables 2 and 3.

To address HA 2 and H02, the personal noise data were compared between the quiet and conventional fleets using a linear mixed model to determine if there was a significant difference in noise exposure between the two types of sites at the different noise criteria (OSHA PEL, OSHA AL, ACGIH TLV). A mixed model was used to account for random effects that may be caused due to repeated measures.

Specific Aim 2 – Characterize noise emissions from oil and gas operations and equipment.

HA 3: Oil and gas extraction equipment noise is greater than or equal to 85 dBA at 1 meter distance or worker location.

H0 3: Oil and gas extraction equipment noise is less than or equal to 84 dBA at 1 meter distance or worker location.

The SA2 hypotheses were addressed by measuring the noise emissions from fracturing equipment during normal operations to determine hazardous noise areas on hydraulic fracturing sites. Noise measurements were taken with a sound level meter (SLM) in the A- and C-weighted scales to measure the equipment sound pressure levels (SPL) at a one-meter distance from the equipment in each cardinal direction, when possible, for a minimum duration of 10 seconds. Worker locations were also measured for a minimum duration of 10 seconds. Octave band analysis (OBA) was performed in tandem with the SPL measurements to determine the dominant noise frequencies. Each noise source was assessed against a threshold of 85 dBA. The noise data collected were averaged when multiple measurements were possible and reported for each piece of equipment or worker location.

<u>Specific Aim 3 – Determine if oil and gas employees suffer from temporary threshold shifts in hearing.</u>

HA 4: Quiet and conventional fracturing employees experience a 10 dB shift or greater in hearing acuity at any frequency.

H0 4: Quiet and conventional fracturing employees do not experience a 10 dB shift in hearing acuity at any frequency.

HA 5: Conventional fracturing employees experience more 10 dB shifts or greater in hearing acuity at any frequency than the quiet fleet.

H0 5: There is no difference of hearing acuity in 10 dB shifts or greater in hearing acuity at any frequency between the quiet and conventional fleets.

The SA3 hypotheses were evaluated by administering pre- and post-shift pure tone audiometric hearing tests on quiet fleet and conventional fracturing workers to determine if these workers experience a TTS (i.e., decrease in hearing) after a work shift. Pre- and post-shift hearing tests were administered onsite by a certified Occupational Hearing Conservationist (OHC). These data were evaluated to determine if there was a hearing shift in 10 dB increments for each tested frequency (500, 1000, 2000, 3000, 4000, 6000, 8000 Hz). To assess HA 5 and H0 5, a mixed logistic regression analysis was run to compare the fleets and see if the conventional fleet had more TTS than the quiet fleet.

One manuscript containing all three aims titled, "Occupational Noise Exposure and Hearing Assessment of Hydraulic Fracturing Workers" was submitted to the *Journal of Occupational and Environmental Hygiene* in December 2023 and is under review. This manuscript is presented in Chapter 2 of this document. Based on the results in the current study, employers may consider implementing a hearing loss prevention program based on NIOSH recommendations to prevent future hearing loss in OGE sector workers.

CHAPTER 2: "OCCUPATIONAL NOISE EXPOSURE AND HEARING ASSESSMENT OF HYDRAULIC FRACTURING WORKERS"[1]

SUMMARY

Oil and gas extraction companies are exempt from implementing hearing conservation programs for their workers according to the Occupational Safety and Health Administration's (OSHA) noise standard. The occupational noise exposure and hearing status of these workers has not been published in scientific literature before the present study, presumably due to this exemption. In this study, area and personal noise exposures and worker hearing acuity were measured at both conventional and quiet hydraulic fracturing fleets, allowing a comparison between the fleets. Quiet fleets refer to the use of engineering controls to decrease noise levels of the pumps while conventional fleets do not employ these measures. In both fleets, the authors conducted personal noise dosimetry, equipment noise measurements, and pure tone audiometry pre- and post-work shift to determine if there were temporary threshold shifts (TTS) in hearing. Based on the personal noise dosimetry results, 42/50 (84%) of the quiet fleet and 34/34 (100%) of the conventional fleet workers sampled were at or over 100% noise dose according to the American Conference of Governmental Industrial Hygienists' (ACGIH) noise Threshold Limit Value (TLV). Based on the OSHA Permissible Exposure Limit (PEL) noise criteria, 9/50 (18%) of the quiet fleet workers and 15/34 (44.1%) of the conventional fleet workers were at or over 100% noise dose. Workers in both fleets experienced TTS, but no significant difference was

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observed between the types of fleets in relation to TTS. Most equipment of both fleets exceeded 85 decibels, but the pumps of the quiet fleet were ~14 dB lower than those of the conventional fleet. Although the quiet fleet noise controls reduced personal noise exposure, a portion of the quiet fleet workers sampled still faced noise levels that could increase the risk of hearing loss. The researchers suggest the initiation of a hearing conservation program despite OSHA exemption to safeguard worker health and recommend workers involved in certain job tasks employ dual hearing protection based on the exposure monitoring results.

INTRODUCTION

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Hydraulic fracturing, or fracking, is the process of injecting water, chemicals, and sand into the ground to fracture shale rock and extract petroleum (King, 2010). Researchers in the current study investigated the noise exposure from two forms of fracking: conventional and quiet fleet. Conventional fracking is hydraulic fracturing without the use of engineered noise controls for the fracking pumps and engines that power the pumps, while quiet fleet fracking uses engineering controls to reduce sound emissions by insulating the fracking pumps and engines that power the pumps. The authors compared quiet fleet and conventional fracking data to determine if these engineering controls were efficient for reducing worker exposure to noise.

In the current study, hydraulic fracturing noise-exposure data and worker hearing status were assessed by (1) performing personal noise dosimetry on OGE workers who perform fracturing job tasks at quiet fleet and conventional fracturing sites; (2) characterizing noise emissions from machinery for conventional and quiet fracturing processes; and (3) administering pre- and post-shift pure tone audiometric hearing tests on quiet fleet and conventional frack workers. Based on the results in the current study, employers may consider implementing a hearing loss prevention program based on NIOSH recommendations to prevent future hearing loss in OGE sector workers.

METHODS

This study was performed at one quiet fleet fracking site in Colorado and one conventional fleet fracking site in Wyoming, both managed by the same oil and gas company that provided the researcher access to the sites. The quiet fleet sampling was performed from June to July 2022, while the conventional fleet sampling was performed over a two-week period during October 2022. Both fleets included two crews that were sampled during both day and night shifts. There was no overlap of workers between the quiet and conventional fleets. Twenty-nine men and one woman participated in the quiet fleet sampling campaign, while 28 men participated in the conventional fleet sampling. Three to six workers were sampled during each work shift.

Worker Recruitment

All aspects of this study were performed in accordance with the human subjects research protocol approved by Colorado State University's Institutional Review Board (#3335). Subjects were recruited at the beginning of the work shift and were over the age of eighteen, English-speaking, and had no occlusion of the ear (perforated eardrum, excessive earwax) as this could have affected audiometric testing results. A nominal incentive was provided to each participating worker after the completion of the post-shift hearing test and noise dosimeter return.

Personal Noise Monitoring

Noise dosimetry was performed using Larson Davis Spark Dosimeters (Model 706 RC, Provo, UT, USA). Calibration occurred before and after sampling at 114 dB using a Larson Davis CAL 150 Precision Acoustic Calibrator (Provo, UT, USA). The noise exposure data were downloaded from the dosimeters using version 6.2.4 Blaze software (Larson Davis; Provo, UT, USA). To ensure accurate noise measurements, the dosimeters were set and used in accordance with the OSHA Technical Manual, Section III, Chapter 5 (OSHA, n.d.). At the beginning of each worker's shift, which was 12-hours, a noise dosimeter was secured to the worker with the microphone attached in the hearing zone (i.e., a 2-foot-wide sphere surrounding the head) on the worker's shoulder or lapel. The workers were instructed to perform their shifts normally and not to shout into the microphone or disturb it. The dosimeters were set to record and returned near the end of the work shift. The personal noise dosimetry samples were evaluated using the 8-hour occupational noise exposure criteria for the OSHA action limit (AL), OSHA permissible exposure limit (PEL), and the American Conference of Industrial Hygienist (ACGIH) threshold limit value (TLV) in order to evaluate their work-shift time weighted average noise exposure.

Thirty workers were monitored for their personal noise exposures in the quiet fleet, 14 of whom were sampled more than once, resulting in 50 personal samples. For the conventional fleet, 27 workers were sampled, 5 of whom were sampled more than once, resulting in 34 personal samples.

Equipment Noise Measurement

Equipment sound pressure levels (SPLs) and frequency spectra in the A, C, and Z-weighted scales were measured using a sound level meter (SLM) and octave band analyzer (OBA) (Larson Davis, Model 831, Provo, UT, USA) and the distance between the measurement location and equipment was documented. When possible, noise measurements were taken at three to four cardinal points around the equipment during idling and fracking operations. Due to the presence of hazards at the conventional site, limited measurements were made. Before and after each sampling event, the SLM was pre- and post-calibrated with a CAL200 Precision Acoustic Calibrator (Larson Davis, Provo, UT, USA) at 94 and 114 dB. Daily environmental conditions including humidity, wind velocity, and temperature were logged using a VelociCalc air velocity meter (Model 9535, TSI Incorporated, Shoreview, MN, USA).

Noise Contour Mapping

The company provided drawings of the frack pad site to the researchers. The A-weighted sound pressure levels measured with the SLM were annotated on printed versions of these drawings. *NoiseAtWork* software (DGMR, Version 2022, Type D, Netherlands) was then used to generate noise contours superimposed onto the drawings.

Audiometry

A certified occupational hearing conservationist (OHC) conducted all audiometric testing and ear inspections. At the onset and conclusion of their work shifts, workers underwent pure-tone audiometric hearing tests to assess any changes in hearing acuity.

Prior to the pre-shift hearing test, an otoscope (Welch Allyn, Skaneateles Falls, NY, USA) was used to examine both ears of each worker. This was done to ensure the tympanic membrane's health (checking for intactness, absence of redness) and to verify that no earwax obstructions were present, as these could compromise the accuracy of hearing test results. If a worker's eardrums were deemed healthy, they were then asked to provide details about their hearing history using an audiometric questionnaire (Appendix A). This questionnaire, developed by Adams et al. (2017), was derived from the U.S. Public Health Service/Federal Occupational Health Audiogram History Report (Adams & Brazile, 2017; Occupational Safety and Health Administration, n.d.-b). The questionnaire captured information on previous noise exposure prior to the test, recreational noise exposures, types of hearing protection used at work, smoking habits, analgesic use, and any relevant medical history related to hearing loss. Upon completing the questionnaire, workers were briefed about the hearing test procedure.

The hearing tests were performed inside a specially designed, sound-attenuating portable booth. This booth, constructed by the researchers, comprised four foamular NGX highperformance XPS insulation project panels (1” x 2’ x 2’) arranged in an open-faced box configuration. Its interior was lined with 17 Berlai acoustic foam panels (12” x 12” x 2”). To ensure stability, four wooden dowels were affixed to the foamular panels, allowing the booth to stand upright. The booth was positioned over a chair, and a blanket was draped over it, offering additional sound insulation, and minimizing distractions for the participant. The booth’s design and setup are depicted in Figures 1a and 1b.

Figure 1a and 1b. Portable booth setup in trailers provided by the company at the (1a) quiet fleet site and (1b) conventional fleet site. This booth was built by researchers to reduce ambient noise for pure-tone audiometry hearing tests. A small rug, carpet tiles, and acoustic panels were used to further reduce noise.

Before pre- or post-hearing tests were performed, the ambient noise was measured inside the booth for an average of 14.0 seconds (ranging from 10.4 to 24.3 seconds) and then uploaded to G4 LD Utility 4.6.2 software. The measured 500, 1000, 2000, 4000, and 8000 Hz octave bands were compared to the OSHA Table D1 for maximum allowable ambient sound levels for the quiet fleet because supra aural earphones were used (Occupational Safety and Health Administration, n.d.-a) (Appendix B). Insert earphones were used in the conventional fleet so the measured 500, 1000, 2000, 4000, and 8000 Hz octave bands were compared to ANSI S3.1-1999 (R2018) Maximum Permissible Ambient Noise Levels (MPANLs), which OSHA permits (OSHA, 2022) (Appendix B). For the quiet fleet, all average frequencies met the OSHA criteria except for 500 Hz, while all average frequencies for the conventional fleet were below the ANSI MPANLs thresholds.

Pure-tone audiometric hearing tests were manually performed with pulsed tone on each ear. A modified Hughson-Westlake Technique was used at the frequencies 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz, with 1000 Hz being tested twice to ensure test reliability (Walker MD, MPH et al., 2013). The OHC tested frequencies in this order, starting with the right ear followed by the left in Hertz (Hz): 1000, 500, 1000, 2000, 3000, 4000, 6000, 8000. The OHC started the decibel level at 40 dB, decreased the tone 10 dB when the worker heard the tone, and increased the tone by 5 dB if the tone was heard. The tone was recorded on an audiometric form when the worker heard the tone two ascending times. The order of the ears was standardized to right then left regardless of hearing deficit.

The quiet fleet subjects were tested using an Earscan 3 ES3S Pure Tone Audiometer (Micro Audiometrics Corporation, Murphy, NC, USA) calibrated to ANSI S3.6-1969 specification with supra-aural transducers attached. The Earscan 3 was biologically checked each day using a TSI Quest Bio-acoustic simulator (Quest Technologies, Model BA-202-25, Oconomowoc, WI, USA). The conventional fleet subjects were tested using a calibrated Inventis Piccolo Speech audiometer (Padova, Italy) with Etymotic Research 3C Insert Earphones (10 Ohm, Elk Grove Village, IL, USA) attached. E-a-RLink 3A Insert Ear tips were used and changed out between each hearing test. A bio-acoustic simulator was used to biologically check the Piccolo Speech audiometer (Model MI-300 Calibration Monitor, Monitor Instruments, Hillsborough, NC, USA) each day testing occurred.

Statistical Analysis

Statistical analyses were conducted using Microsoft Excel and RStudio, an interface for R (Boston, MA, version 2022.07.2). Personal noise dosimetry data were described using statistics by job task, including mean, standard deviation (SD), and percentage overexposed. A linear mixed model was employed to compare dosimetry noise exposures between the conventional and quiet fleets based on three criteria: OSHA AL, OSHA PEL, and ACGIH TLV. This mixed model was selected to account for random effects, given the study's repeated measures. The equipment noise data, as measured by the sound level meter, were benchmarked against the OSHA Action Level of 85 dBA using slow response. TTS was characterized by the proportion of workers showing a hearing acuity shift of ≥ 10 dB at any frequency. Hearing recovery was defined as shifts of ≤ -10 dB at any frequency. A mixed logistic regression analysis was utilized to compare TTS and hearing recovery outcomes between the conventional and quiet fleets.

RESULTS

Personal Noise Monitoring

Personal noise dosimetry sampling was performed on workers performing a variety of tasks. The job tasks and their descriptions are provided in Table 1. The average noise dosimetry sampling duration was 8 hours and 31 minutes for the quiet fleet workers, and 8 hours and 48 minutes for the conventional fleet workers. Results from the noise dosimetry, categorized by job tasks and criteria (OSHA AL, OSHA PEL, ACGIH TLV), can be seen in Tables 2 and 3. As detailed in Table 3, workers of the conventional fleet generally experienced a higher proportion of overexposure (noise doses of 100% or more) compared to those in the quiet fleet.

The linear mixed model statistical analysis revealed significant differences in noise levels between the conventional and quiet fleets across all three criteria: OSHA AL (p-value = 0.007), OSHA PEL (p-value = 0.002), and ACGIH TLV (p-value = 0.001). These results indicate, with 95% confidence, that the conventional fleet workers faced considerably higher noise exposure compared to their quiet fleet counterparts across all evaluated criteria.

Equipment

The equipment noise measurement results are presented in Tables 4 and 5. Noise levels of equipment increased during fracturing and decreased while idling. Idling equipment noise in the quiet fleet (excluding worker enclosures) ranged from 52.0 – 89.0 dBA and during fracturing operations the equipment noise ranged from 81.7 – 99.2 dBA. Idling equipment noise in the conventional fleet (excluding worker enclosures) ranged from 84.1 – 101.4 dBA while during fracturing operations the equipment noise ranged from 93.9 – 113.1 dBA.

Both the quiet and conventional fleets registered the highest noise levels at the

Table 1. Description of fracking job tasks.

Job task	Description of tasks
Chemical operator	Ensures proper chemical delivery from container to chemical pumps.
Crew lead	Supervisor; helps where needed and is all over the location.
Ground boss	Keeps horsepower pumps maintained; opening and closing the wellhead; keeping the iron safe and monitoring for leaking.
Ground walker	Assist in pump maintenance and general housekeeping.
Hydro operator	Running combo unit operates from the cab of unit; mixing water and chemicals.
Forklift/ Sand Pusher	Loading and off-loading sand boxes; opening and closing sand boxes.
Sand operator	Mixing sand from enclosed unit.
Pump walker	Assists ground boss in day-to-day operations.
Pump down	Operates pumps to work directly with wireline company to perforate well.
Mechanic	Maintain and repair trucks and equipment on the job site as needed.
Electrician operator	Works on computers, electrical, printers, and programming; keeps electronics of the pumps functioning.
Float	Performs a mix of job tasks as needed.
Blender operator	Operates equipment to blend the proper concentrations of water, chemical additives, and sand to pump into well.
Safety	Reviews written logs and ensures compliance with safety policies.

horsepower pumps (99.2 dBA, 113.1 dBA), T-belt (91.9 dBA, 98.9 dBA), manifold (92.2 dBA, 101.8 dBA), blender (92.1 dBA, 103 dBA), and outside the sand box (88.4, 99.3 dBA). The most prominent octave frequency band of both fleets was 31.5 Hz, or low frequency noise.

Noise Contour Mapping

The noise contour map for the quiet fleet is displayed in Figure 2 and the conventional fleet in Figure 3. The loudest areas for both fleets were around and between the pumps (e.g., horsepowers). Of particular note is that the quiet fleet noise did not exceed 110 dBA, whereas the conventional fleet noise did exceed 110 dBA. The acoustical barrier wall used in the quiet fleet appeared to be effective at attenuating noise levels.

Audiometry

TTS (i.e., decrease in hearing acuity) and recovery (i.e., increase in hearing acuity) occurred in both fleets. Proportions of TTS and recovery are displayed in supplementary Table S1 in Appendix C. The highest proportion of TTS was in the quiet fleet at 6000 and 8000 Hz in the right ear (20.0%) and 6000 Hz in the left ear (22.9%). The largest proportion of recovery was in the left ear of the quiet fleet at 6000 Hz (17.1%). Though TTS and recovery occurred in both fleets in both ears in most frequencies, a higher proportion of TTS occurred than recovery.

Statistical analysis indicated no significant difference between TTS and fleet type at any frequency in either ear. There was no significant difference between hearing recovery and fleet type at any frequency in either ear. Results of the analysis are shown in supplementary Table S2 in Appendix C.

Pre-shift audiograms were used to characterize the percentage of hearing loss per fleet. The initial audiogram was used for this purpose and repeated pre-shift audiograms for the same worker were excluded. This analysis excluded the frequency 500 Hz for the quiet fleet as this was above OSHA Table D1 maximum allowable ambient sound levels; the conventional fleet maximum sound levels were below the threshold but excluded for comparison. Non-recordable decibels recorded at any frequency were excluded for analysis. The amount of hearing loss (≥ 26 dB) in at least one frequency in either ear was 65% (13/20) for the quiet fleet and 79% (22/28) for the conventional fleet.

Audiometric Questionnaire

Results for the audiometric questionnaire are presented in Table 6. For medical history, the history of hearing loss was marginally higher in the conventional fleet a (17.9%) than in the quiet fleet at (10%). Ototoxicant use recorded in the survey included analgesics and current

Table 2. Noise exposure among hydraulic fracturing workers (repeated measures) in the quiet fleet.

	Task Evaluated	Workers assessed per task	OSHA AL			OSHA PEL			ACGIH TLV		
			Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hour shift	Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hr shift	Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hr shift
		Number	Percent (SD)	dBA (SD)	Number (%)	Percent (SD)	dBA (SD)	Number (%)	Percent (SD)	dBA (SD)	Number (%)
Quiet Fleet	Blender operator	1	97.0	90.9	1 (100)	71.1	88.7	0 (0)	353.2	91.2	1 (100)
	Chemical operator	2	76.1 (33.7)	88.8 (3.2)	2 (100)	56.9 (36.1)	86.2 (4.8)	1 (50.0)	336.9 (153.8)	90.7 (2.0)	2 (100)
	Crew lead	8	67.0 (36.4)	87.6 (4.3)	5 (62.5)	49.2 (36.7)	83.1 (6.4)	1 (12.5)	535.2 (474.8)	90.9 (4.0)	7 (87.5)
	Electrician technician	1	12.5	74.3	0 (0)	5.5	68.3	0 (0)	45.0	81.1	0 (0)
	Float	5	77.7 (24.2)	88.1 (2.0)	5 (100)	58.6 (22.9)	86.0 (2.5)	0 (0)	381.5 (160.5)	90.7 (1.5)	5 (100)
	Ground boss	7	69.2 (43.8)	86.9 (4.9)	5 (71.4)	51.5 (44.0)	83.4 (7.5)	1 (14.3)	377.7 (385.8)	89.8 (4.1)	6 (85.7)
	Ground walker	3	62.5 (10.3)	87.2 (2.6)	3 (100)	44.1 (13.6)	84.5 (3.2)	0 (0)	375.1 (167.4)	90.9 (2.5)	3 (100)
	Hydro operator	6	30.5 (19.4)	80.8 (4.6)	2 (33.3)	13.9 (18.5)	72.5 (7.4)	0 (0)	133.3 (138.5)	85.0 (3.8)	4 (66.7)
	Mechanic	3	180.2 (161.9)	92.6 (5.8)	3 (100)	172.3 (166.6)	91.9 (6.3)	1 (33.3)	5504.0 (4404.8)	100.0 (6.9)	3 (100)
	Pump walker	10	158.1 (263.1)	89.7 (7.1)	9 (90.0)	142.5 (265.7)	87.6 (8.3)	4 (40.0)	3042.4 (7362.5)	94.1 (6.7)	10 (100)
	Pump down	2	11.0 (0.6)	73.4 (2.5)	0 (0)	5.0 (0.1)	67.8 (2.3)	0 (0)	37.5 (4.6)	80.4 (1.8)	0 (0)
	Sand operator	1	18.2	77.1	0 (0)	12.0	74.1	0 (0)	79.8	83.6	0 (0)
	Sand pusher	1	128.3	93.2	1 (100)	104.0	91.7	1 (100)	1033.2	96	1 (100)
	All tasks	50	86.6 (130.1)	86.6 (6.4)	36 (72.0)	70.4 (131.4)	83.0 (8.7)	9 (18.0)	1199.1 (3633.2)	90.5 (6.0)	42 (84.0)

OSHA AL = Action level of 85 dBA, OSHA PEL = Permissible exposure limit of 90 dBA, ACGIH TLV = Threshold limit value of 85 dBA, SD= Standard deviation, TWA = Time weighted average, dBA = decibel in A-weighted scale

Table 3. Noise exposure among hydraulic fracturing workers (repeated measures) in the conventional fleet.

	Task Evaluated	Workers assessed per task	OSHA AL			OSHA PEL			ACGIH TLV		
			Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hour shift	Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hr shift	Mean noise dose	Mean 8-hr TWA	Workers overexposed 8-hr shift
		Number	Percent (SD)	dBA (SD)	Number (%)	Percent (SD)	dBA (SD)	Number (%)	Percent (SD)	dBA (SD)	Number (%)
Conventional Fleet	Blender operator	2	154.7 (102.0)	91.3 (6.0)	2 (100)	133.1 (112.4)	89.5 (7.9)	1 (50)	1096.0 (1000.5)	93.6 (5.2)	2 (100)
	Chemical operator	6	271.3 (401.0)	92.6 (7.7)	5 (83.3)	258.0 (403.1)	91.6 (8.4)	3 (50)	6757.7 (13798.4)	97.5 (6.5)	6 (100)
	Crew leader	2	45.1 (12.5)	85.4 (1.5)	1 (50)	36.0 (8.0)	84.0 (0.8)	0 (0)	442.5 (32.2)	92.2 (0)	2 (100)
	Electrician technician	1	16.6	78.1	0 (0)	12.4	76.0	0 (0)	260.3	89.8	1 (100)
	Float	6	100.1 (27.4)	90.1 (2.5)	6 (100)	79.8 (30.2)	88.3 (3.5)	2 (33.3)	684.4 (249.2)	93.3 (2.2)	6 (100)
	Frac operator	1	74.8	88.7	1 (100)	35.0	83.2	0 (0)	282.2	90.0	1 (100)
	Ground Boss	2	359.9 (232.4)	99.3 (4.4)	2 (100)	349.3 (230.8)	99.0 (4.5)	2 (100)	9026.0 (9187.6)	103.5 (5.2)	2 (100)
	Mechanic	1	193	96.1	1 (100)	185.3	95.8	1 (100)	7435.9	104.5	1 (100)
	Pump walker	8	133.7 (84.3)	92.0 (4.8)	8 (100)	121.2 (84.5)	90.9 (5.4)	4 (50)	1575.0 (1165.7)	96.5 (3.5)	8 (100)
	Safety	1	102.4	90.7	1 (100)	91.3	89.8	0 (0)	1535.0	97.2	1 (100)
	Sand operator	3	102.2 (5.0)	90.7 (0.5)	3 (100)	80.3 (8.3)	89.0 (0.8)	1 (33.3)	567.5 (102.8)	92.8 (0.7)	3 (100)
	Sand pusher	1	82.6	92.0	1 (100)	53.9	88.9	0 (0)	462.5	93.7	1 (100)
	All tasks	34	152.7 (188.8)	91.2 (5.4)	31 (91.2)	136.8 (190.7)	89.8 (6.2)	15 (44.1)	2648.8 (6348.6)	95.6 (4.8)	34 (100)

OSHA AL = Action level of 85 dBA, OSHA PEL = Permissible exposure limit of 90 dBA, ACGIH TLV = Threshold limit value of 85 dBA, SD= Standard deviation, TWA = Time weighted average, dBA = decibel in A-weighted scale

Table 4. Quiet fleet equipment area noise measurements while fracturing (9 pumps running each side) or idling. Red = ≥ 85 dBA.

Fleet Type	Equipment/Location	Idle/ Fracturing (frac)	SPL A (dBA)	SPL C (dBC)	OBA Range	Predominant Frequency Band (Hz)	Distance	Over 85 dBA?
Quiet	Horsepower- front of cab	idle	71.8	87.0	low	63	1 meter	no
		frac	87.4	97.4	normal	125	1 meter	yes
	Horsepower- between two pumps	idle	81.1	89.3	low	31.5	0.3 meter	no
		frac	99.2	106.6	normal	125	0.3 meter	yes
	Horsepower- one pump	idle	74.1	-	-	-	1 meter	no
		frac	90.2	98.1	normal	125	1 meter	yes
	Blender- inside unit	idle	71.1	84.7	low	31.5	worker location	no
		frac	80.3	91.7	normal	63	worker location	no
	Blender- outside unit	idle	85.0	91.5	low	31.5, 63	1 meter	yes
		frac	92.1	98.9	normal	125	1 meter	yes
	Blender- door of unit open	idle	-	-	-	-	-	-
		frac	87.9	97.3	normal	31.5	worker location	yes
	T-belt	idle	89.0	94.3	low	63	1 meter	yes
		frac	91.9	99.3	normal	63	1 meter	yes
	Sand box- inside unit	idle	70.4	83.3	low	31.5	worker location	no
		frac	70.8	87.1	normal	63	1 meter	no
	Sand box- outside unit	idle	-	-	-	-	-	-
		frac	88.4	93.8	normal	500	1 meter	yes
	Manifold	idle	74.5	-	-	-	-	no
		frac	92.2	99.6	normal	250	location	yes
	Hydro- inside	frac	70.8	83.9	normal	31.5	worker location	no
	Hydro- outside	frac	84.2	95.0	normal	31.5	1 meter	no
	Pump down- front of cab	idle	52.0	-	-	-	-	no
		frac	81.7	90.8	normal	31.5	1 meter	no
	Pump down- side	idle	57.0	-	-	-	-	no
		frac	87.1	93.2	normal	31.5	1 meter	yes

*Measurements were taken with 9 running pumps per side for 18 pumps running total. Predominant frequency is based on (1/1) octave band frequency spectrum.

SPL = Sound Pressure Level, OBA = Octave Band Analysis, dBA = decibels in A-weighting scale, dBC = decibels in C-weighting scale, Hz = Hertz

Table 5. Conventional fleet equipment area noise measurements while fracturing (9 pumps running each side) or idling. Red = ≥ 85 dBA.

Fleet Type	Equipment/Location	Idle/ Fracturing (frac)	SPL A (dBA)	SPL C (dBC)	OBA Range	Predominant Frequency Band (Hz)	Distance	Over 85 dBA?
Conventional	Loud horsepower- front of cab	idle	88.8	94.6	normal	31.5	1 meter	yes
		frac	93.9	105.4	normal	125	1 meter	yes
	Loud horsepower- between two pumps	idle	101.4	103.8	normal	63	0.3 meter	yes
		frac	113.1	116.1	normal	125	0.3 meter	yes
	Loud horsepower- pump	idle	94.2	97.5	normal	31.5	1 meter	yes
		frac	104.6	108.9	normal	125	1 meter	yes
	Blender- inside unit	idle	76.3	90.8	normal	31.5	worker location	no
		frac	89.3	101.4	normal	125	worker location	yes
	Blender- outside unit	idle	86.6	96.2	normal	31.5	1 meter	yes
		frac	103.0	110.0	normal	125	1 meter	yes
	Blender- door of unit open	idle	-	-	-	-	-	-
		frac	96.1	105.2	normal	31.5	worker location	yes
	T-belt	idle	98.8	102.2	normal	31.5	1 meter	yes
		frac	98.9	107.3	normal	250	1 meter	yes
	Sand box- inside unit	idle	66.3	85.2	normal	31.5	worker location	no
		frac	81.0	93.7	normal	125	1 meter	no
	Sand box- outside unit	idle	96.0	101.5	normal	31.5	1 meter	yes
		frac	99.3	106.5	normal	250	1 meter	yes
	Manifold	idle	84.1	98.7	normal	31.5	location	no
		frac	101.8	111.1	normal	125	location	yes

*Measurements were taken with 9 running pumps per side for 18 pumps running total. Predominant frequency is based on (1/1) octave band frequency spectrum.

SPL = Sound Pressure Level, OBA = Octave Band Analysis, dBA = decibels in A-weighting scale, dBC = decibels in C-weighting scale, Hz = Hertz

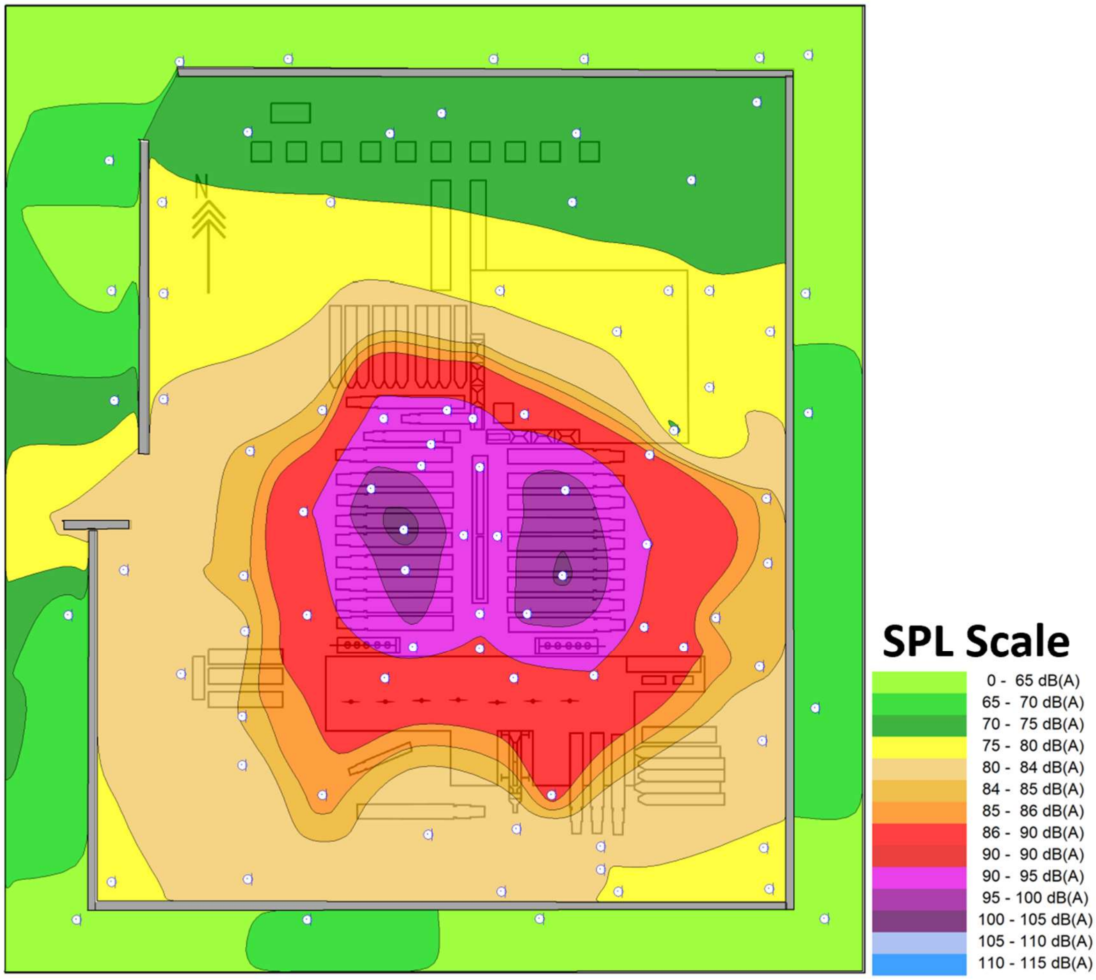

Figure 2. Quiet fleet noise map. Areas where noise measurements were taken are marked with dots. The grey line indicates where the acoustical barrier wall was erected. A sound pressure level (SPL) scale is to the right of the map. The OSHA action criterion level is reached and exceeded in dark orange (85-86 dBA) and red (86-90 dBA) areas and above. The OSHA PEL criterion level is reached at 90 dBA (dark red) and exceeded at 90-95 dBA (light purple), 95-100 dBA (purple), 100-105 dBA (dark purple), 105-110 dBA (light blue), and 110-115 dBA (dark blue). An acoustical wall was present at this site.

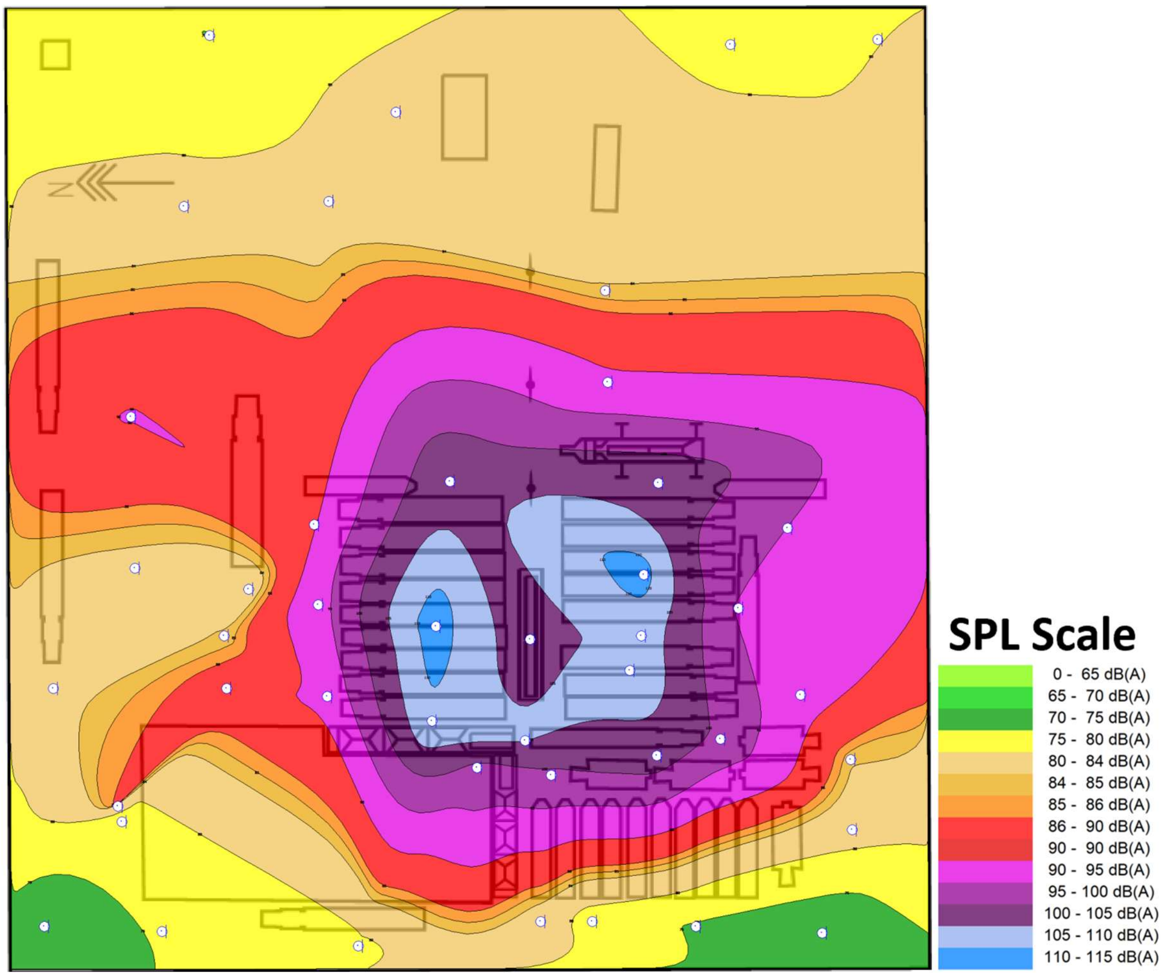

Figure 3. Conventional fleet noise map. Areas where noise measurements were taken are marked with dots. A sound pressure level (SPL) scale is to the right of the map. The OSHA action criterion level is reached and exceeded in dark orange (85-86 dBA) and red (86-90 dBA) areas and above. The OSHA PEL criterion level is reached at 90 dBA (dark red) and exceeded at 90-95 dBA (light purple), 95-100 dBA (purple), 100-105 dBA (dark purple), 105-110 dBA (light blue), and 110-115 dBA (dark blue). No acoustical wall was in place for this site.

smoking. More workers in the conventional fleet reported taking analgesics in the past 7 days (53.6%) compared to the quiet fleet (35.0%). Current smoking of tobacco was similar between the fleets (conventional = 17.9%, quiet = 10%). A large difference was observed in the history of ringing ears (39.3% of the conventional fleet workers versus 0% in the quiet fleet). HPD reported use at work was comparable, with 100% of the quiet fleet and conventional fleet at 96.4%. When

Table 6. Audiogram questionnaire results.

		Quiet Fleet (n = 20)	Conventional Fleet (n = 28)
		Number (%)	**Number (%)**
Social noise exposure and HPD use	Loud music	15 (75.0)	22 (78.6)
	Loud music – wear HPD	3/15 (20.0)	1/22 (4.5)
	Firearms	13 (65.0)	25 (89.2)
	Firearms – wear HPD	12/13 (92.3)	20/25 (80.0)
	Power tools	16 (80.0)	21 (75.0)
	Power tools – wear HPD	4/16 (25.0)	6/21 (28.6)
	Heavy machinery	11 (55.0))	19 (67.9)
	Heavy machinery – wear HPD	8/11 (72.7)	11/19 (57.9)
	Motorcycles	7 (35.0)	10 (35.7)
	Motorcycles – wear HPD	NA	NA
Medical	Analgesics in past 7 days	7 (35.0)	15 (53.6)
	Prior military	2 (10.0)	6 (21.4)
	History of hearing loss	2 (10.0)	5 (17.9)
	Family history of hearing loss	1 (5.0)	3 (10.7)
	History of ear infections	0	1 (3.6)
	Current cold, flu, or allergy	2 (10.0)	2 (7.1)
	Current smoking	2 (10.0)	5 (17.9)
	History of hearing aid	0	2 (7.1)
	History of ringing ears	0	11 (39.3)
	History of recurring impacted ear wax	0	3 (10.7)
	History of head injury	0	5 (17.9)
	Wear HPD at work	20 (100.0)	27 (96.4)

HPD = Hearing protection device

examining social noise exposure and the use of HPD, a sizeable proportion of both fleets' workers reported usage of firearms (quiet = 65.0%, conventional = 89.2%). However, reported HPD use of the workers who shot firearms was higher among the quiet fleet (92.3%) than the conventional fleet (80.0%).

DISCUSSION

Personal Dosimetry

Based on the personal dosimetry results, the quiet fleet controls were effective at decreasing personal noise exposures. For example, 18% of quiet fleet workers were at or overexposed to the OSHA PEL, yet 44% of conventional workers were at or overexposed to the

OSHA PEL. In the quiet fleet, the mechanic and sand pusher were over the OSHA PEL while all other job tasks were under 90 dBA TWA. For the conventional fleet, several tasks were at or over the PEL: the blender, chemical, ground boss, mechanic, pump walkers, and safety. The mechanic job task overlapped these two fleets as being over the PEL. Given these overexposures, additional discussion on adequate hearing protection is found in the "Recommendations" section of this paper.

Not all job tasks were monitored for each fleet as monitoring was based on available worker volunteers and also the equipment being used at the time of monitoring. Overlapping job tasks included the blender operator, chemical operator, crew lead, electrician technician, float, ground boss, and mechanic. Job tasks that were measured in one fleet but not the other included the ground walker, hydro operator, pump down, safety, and frac operator. The pump down and hydro operator were job tasks only in the quiet fleet for this sampling period as the conventional fleet did not have sump pumps or hydro equipment.

Equipment

Overall, the conventional fleet was louder than the quiet fleet during both idling and fracturing operations. The quiet fleet attenuated pump design decreased worker and area noise exposure when compared to conventional fleet equipment. The engineering controls used to reduce the pump noise should be used whenever possible.

Several work areas were inside enclosures and included the blender, sand box, and hydro cabins in which the noise levels were measured. In general, noise measurements taken inside these enclosed spaces had relatively lower noise levels when compared to outside noise levels; thus, these enclosures offered noise protection to the workers who performed operations within the enclosures.

During quiet fleet fracturing, the noise level (one measurement taken per location) outside of the blender cabin was measured at 92.1 dBA, whereas the noise level inside the blender cabin at the worker location with the door closed was measured at 80.3 dBA; and inside with the door open was 87.9 dBA. While the cabin offered ~4 dBA noise attenuation with the door open, having the door closed decreased the noise level to less than 85 dBA. The same noise measurements were taken at the conventional fleet during fracturing: 103 dBA outside of the blender cabin, 89.3 dBA inside the blender cabin at the worker location, and 96.1 dBA inside the blender cabin at the worker location with the door open. Based on these results, it is expected that employees working in the cabin with the door closed would be exposed to noise levels below the OSHA PEL, however while working with the cabin door open or being outside of the blender could result in worker overexposure to noise.

In addition, the sand box enclosure provided substantial noise protection to the sand operator during fracturing operations for both the quiet and conventional fleets. The quiet fleet outside measurement was 88.4 dBA versus 70.8 dBA inside the enclosure; and the conventional fleet outside measurement was 99.3 dBA versus 81.0 dBA inside the enclosure.

Likewise, the hydro enclosure interior noise level at the quiet fleet was measured at 70.8 dBA versus an exterior noise level of 84.2 dBA, approaching the OSHA AL if the equivalent noise level were present for 8 hours (note: the hydro was not in operation at the conventional fleet during sampling). In general, all of the enclosures that were measured (blender, sand box, hydro) provided excellent noise protection for workers inside the enclosures during fracturing operations.

When compared to the Canadian WorkSafe BC bulletin, the equipment noise had similar values (WorkSafeBC, n.d.-b). This bulletin listed noise levels for “fracturing” and “pump trucks” but did not include distances from equipment or locations. The noise levels for fracturing ranged from 104-107 dBA, while pump trucks ranged from 112-116 dBA; for this study, pumps of the conventional fleet were measured up to 113.1 dBA, which falls within this range. After a review of literature, there were no similar studies to the current one to further compare equipment, audiometry, or personal dosimetry results.

Temporary Threshold Shift (TTS)

Even though the conventional fleet site had higher levels of measured noise demonstrated by the personal dosimetry results and equipment measurements, there was no significant difference of TTS (hearing acuity decrease) between the workers in the two fleets. In the right ear, the most affected frequencies were 6000 and 8000 Hz, with 7 workers experiencing TTS in both these frequencies. In the left ear, 8 workers (22.9%) experienced TTS at 6000 Hz. For the conventional fleet, the most TTS presented in the left ear at 500 Hz, where 6 workers (17.1%) presented a shift.

It was noted that workers associated with the quiet fleet had a higher proportion of TTS when compared to those in the conventional fleet. This may be attributed to a misinterpretation by workers of the term "quiet" fleet, potentially resulting in a less vigilant use of HPD. It has also been suggested that workers that are exposed to higher levels of noise wear their HPD more than quieter but still considered hazardous levels of noise due to a false sense of security (Fauzan et al., 2023). Despite this name, quiet fleet sites still presented hazardous noise levels, and the consistent use of HPD remains vital.

Hearing Protection Devices

During the sampling campaign, workers were observed wearing HPDs incorrectly, which could be attributable to a lack of knowledge of proper HPD use. For example, workers were observed wearing hooded sweatshirt hoods or balaclavas under the HPD, which would impair the seal of the earpiece, reducing protection from noise. Also, workers were observed shifting earmuffs to the sides of their heads in hazardous noise areas to communicate, exposing their hearing to hazardous noise. These types of inappropriate HPD usage should be addressed by providing proper HPD use training to reduce potential hazardous noise exposures.

Limitations

Noise maps and personal dosimetry results represent the days the measurements were taken. Different operations, number of pumps running, equipment, and site layout could result in different noise levels.

The PEL, AL, and TLV personal noise measurements account for an 8-hour TWA exposure to compare to 8-hour TWA regulatory exposure limits and not the actual length of the workers' 12-hour shifts. It was assumed by the researchers that the remaining 4 hours of shift time would result in similar exposures as the previous 8-hours.

Workers were not hearing tested immediately before and after shifts but instead were tested within the first 2 to 3 hours of the 12-hour shift start time and within two hours of the end of the shift due to requisite employ tasks. As such, a TTS could have already occurred before the first hearing test. Many of the workers, especially those that participated in the study multiple days, were already exposed to loud noise during the past 48 hours, as the workers in both fleets work in 2-week hitches. Only 3/35(8.5%) of the audiograms for the quiet fleet had no loud exposures within 48 hours and 8/35 (22.9%) of the conventional fleet; this previous loud noise exposure could affect TTS results, or TTS that have previously occurred for a former workday may still be recovering.

Another limitation is that the workers were not tested within a commercially available audiometric booth. Despite this limitation, however, all ambient noise levels were appropriate for hearing tests except for 500 Hz for the quiet fleet due to supra-aural earphone use. Though the fleets were tested using different audiometers and earphone types, test results are still comparable.

Further, hearing test data are not static and worker familiarity with audiometric exams, motivation, and other factors can influence exam accuracy (Chan, n.d.). While a larger TTS cannot predict a larger increase in permanent hearing loss, the very presence of a TTS is a risk of developing permanent hearing loss.

Hearing loss is defined by the American Academy of Otolaryngology (AAO) as a hearing level of 25 dB at 500, 1000, 2000, and 3000 Hz, with a growth rate for impairment of permanent threshold shifts (PTA) at 1.5% per decibel (American Academy of Otolaryngology, 1979; Ryan et al., 2016). The American Speech-Language-Hearing Association (ASHA) also has criteria for calculating hearing loss of 25 dB at 1000, 2000, 3000, and 4000 Hz with a grow rate for impairment for PTA at 2% per decibel (Association, 2024; Ryan et al., 2016). AAO is different than other hearing loss criteria, such as ASHA, in that it uses the low frequency of 500 Hz in the calculation of hearing loss (Ryan et al., 2016).

Because of different criteria for measuring hearing shifts, a limitation of this study is the possibly of having false positives due to the method chosen. For this study, TTS was defined as a 10 dB shift in any frequency in either ear, as was done in studies of TTS in hockey players by Adams et al. study (Adams et al., 2016; Adams & Brazile, 2017). Moreover, a 10 dB shift from baseline is considered a consistent measurement for TTS and permanent threshold shifts (Ryan et al., 2016). In contrast, a standard threshold shift (STS) is considered significant hearing loss and is defined by OSHA to be an increase in hearing level of at least 10 dB in the averaged frequencies of 2000, 3000, and 4000 Hz in the same ear when compared to the baseline audiogram (*1910.95 - Occupational Noise Exposure. | Occupational Safety and Health Administration*, n.d.). Conversely, NIOSH defines a STS as an increase of 15 dB in hearing threshold level at 500, 1000, 2000, 3000, 4000, or 6000 Hz in either ear after two consecutive audiometric tests (National Institute for Occupational Safety and Health, 2023). If the OSHA STS definition was implemented in this study, the number of TTS in this study would likely reduce, meaning there could be false positives in this study when considering this criterion. However, research has suggested that OSHA's STS definition would not fully measure hearing loss caused by ototoxicants (Beaver & Schneider, 2023).

Ototoxicants, or "ear poisons," are chemicals that can harm hearing through exposure to the chemical alone or in combination with noise (OSHA & NIOSH, 2018). Some ototoxicants can cause hearing loss on their own, while other ototoxicants are synergistic with noise exposure (ACGIH, 2020; Campo et al., 2014; OSHA & NIOSH, 2018). It is suspected that oil and gas extraction workers are exposed to ototoxicants (AIHA, 2023). While this study marginally addressed ototoxicant exposure through the audiometric questionnaire, such as cigarette smoking and analgesics, an aspect not considered or measured in this study that could affect hearing levels is onsite fracturing ototoxicants such as toluene, ethylbenzene, lead, carbon monoxide, and xylene (Beaver & Schneider, 2023; Khan, 2011; McDonald-Buller et al., 2021; Morata et al., 1994). Toluene and ethylbenzene are examples of ototoxicants at oil and gas sites that can cause hearing damage on their own without noise exposure (Beaver & Schneider, 2023). onsite ototoxicants and their effects on hearing were not accounted for in this study, meaning the effect of hearing damage risk for the workers studied could be amplified with or without exposure to hazardous noise levels, confounding study results. For example, Morata et al. (1993) studied printing workers exposed to both noise and toluene (Morata et al., 1993). To determine the effects of noise and toluene on hearing, Morato et al. (1993) compared three groups of workers to these printing workers, and the three groups were as follows: (1) workers exposed to noise only, (2) workers exposed to an organic solvent mixture, and (3) workers not exposed to noise, toluene, or solvent mixture. They found that the adjusted relative risk estimates were four times greater for the noise exposed group, five times greater for the organic solvent exposed groups, and eleven times greater for the printers, which were the noise and toluene exposed group; this study demonstrates the synergistic effect of noise and ototoxins (Morata et al., 1993, 1994). In this current study, there were workers that suffered TTS without being exposed to hazardous levels of noise as these workers were wearing HPD, which brought noise exposure to an acceptable level; this could point to ototoxicants exposure.

Ototoxicant exposure does not currently have mandatory regulation requirements but does have several recommendations. As the current OSHA noise standard does not consider ototoxicants, meaning noise standard level protections could contribute still contribute to occupational hearing loss at oil and gas sites (Themann & Masterson, 2019). OSHA recommends but does not have the requirement that the OSHA noise PEL should be used along with ototoxic chemical OELs, but that hearing may still be affected when under the OSHA PEL or chemical OEL (OSHA & NIOSH, 2018). When ototoxicants are present in a workplace, ACGIH recommends adding workers to a HCP, regardless of noise exposure, when an ototoxic chemical reaches 20% of the occupational exposure limit (OEL) or TLV of that chemical exposure (ACGIH, 2020). Outside the US, Safe Work Australia recommends a noise OEL of 80 dBA or lower for workers exposure to ototoxic chemicals (Hemmativaghef, 2020; SAIF, 2020). These recommendations should be considered when attempting to protect workers from suspected ototoxicants. For future research, personal sampling of workers for chemicals such as n-hexane, toluene, xylene, and ethylbenzene, all of which can be found in vapors and gases in oil and gas operations, could provide more information on if these workers are at hearing damage risk (Lawson et al., 2019; Morata et al., 1994).

CONCLUSIONS

This study addresses a significant gap in research pertaining to noise and hearing status in the OGE sector, specifically hydraulic fracturing. This study compared the noise levels and the presence of TTS between the quiet and conventional fleets to evaluate the effectiveness of the engineering controls of the quiet fleet in protecting worker health. While these controls reduced the occupational exposure levels of the quiet fleet workers significantly more than the conventional fleet (OSHA AL p-value = 0.0070, OSHA PEL p-value = 0.0017, ACGIH TLV p-value = 0.0011), hazardous noise levels still remained present in the "quiet" fleet. As both fleets experience hazardous noise, the proper use and training for HPDs are necessary but are not currently mandated by the OSHA noise standard due to exemptions.

Although this study offers foundational information, further research is needed. The suspected exposure of these workers to onsite ototoxicants presents an added layer of concern; the synergistic effects of such chemicals, in conjunction with noise, could amplify hearing damage. A comprehensive approach to address these combined potential risks is crucial for ensuring worker safety.

RECOMMENDATIONS

Personal Noise Exposure

To determine appropriate hearing protection devices (HPD) for the average TWA measured for each job task and whether dual hearing protection should be used, the equations for single protection (Equation 1) and dual protection (Equation 2) were used with an OSHA 50% protection factor. The protection factor is applied as HPD is rarely worn correctly and the protection factor accounts for noise attenuation lost through imperfect use. These equations are found in Appendix F of the OSHA Technical Manual Section 3 Chapter 5 (OSHA, n.d.). The 50% derating cannot be applied for determining adequacy of hearing protector attenuation [29 CFR 1910.95 (j)(1)] but can be applied when considering if implementing engineering controls is required [29 CFR 1910.95 (b)(1)].

<u>Single Protection Equation</u>

Estimated Exposure (dBA) = TWA (dBA) – [(NRR – 7) x 50%] Equation 1

<u>Dual Protection Equation</u>

Estimated Exposure (dBA) = TWA (dB–) - {[(NR–h - 7) x 50%] + 5} Equation 2

<u>Where:</u>

NRR = Noise reduction rating (NRR)

NRRh = Highest NRR of the two hearing protection devices

TWA = Time-weighted average

Single Protection refers to wearing one HPD (such as earplugs or earmuffs) and Dual Protection refers to wearing two HPD (such as both earplugs and earmuffs at the same time). See Tables 7 and 8 for compliance of regulatory standard for implementing adequate engineering controls [29 CFR1910.95(b)(1)] using an HPD NRR of 23, which was observed in use during the current study, and the calculated exposure levels at the AL, PEL, and TLV.

Regulatory Concern (PEL)

The oil and gas extraction sector are required to comply with the OSHA PEL of 90 dBA as an 8-hour TWA [29 CFR 1910.95(b)]. Hearing protection devices are required to reduce noise exposure at the wearer's ear to 90 dBA, and derating can be calculated using Appendix B of the noise standard. In the quiet fleet, the mechanic and sand pusher noise exposures exceeded the PEL while all other job tasks were less than 90 dBA; however, with the HPD headsets used on site, the estimated exposure levels at the employees' ears with a 50% correctional factor were calculated at 83.9 dBA and 83.7 dBA, respectively. For the conventional fleet, several tasks exceeded the PEL: the blender, chemical operator, ground boss, mechanic, pump walkers, and safety. The HPD headsets bring the estimated exposure levels at the employees' ears for these job tasks below the OSHA PEL in all *except for the ground boss*; the average ground boss exposure decreased from 99.0 dBA to 91.0 dBA at the ear with HPD use. This finding suggests that implementing more engineering controls is required to reduce noise exposure to 90 dBA at the ear for the ground boss [29 CFR 1910.95(b)(1).

Best Practice (TLV)

The ACGIH TLV (85 dBA as an 8-hour TWA) is not a regulatory standard but is considered a "best practice" approach. The job tasks that exceeded the noise TLV for the quiet fleet include blender operator, chemical operator, crew lead, ground boss, ground walker, hydro operator, mechanic, pump walker, and sand pusher. With the current hearing protection and a 50% correctional factor, all job tasks except for the mechanic, pump walker, and sand pusher decreased the estimated exposure below the TLV of 85 dBA. To reduce the mechanic, pump walker, and sand pusher exposures below the allowable exposure of 85 dBA, earplugs with a minimum NRR of 33 should be worn with the current HPD headsets.

All job tasks in the conventional fleet exceeded the TLV. The current hearing protection brought the estimated exposure at the ear below the TLV for the crew lead, electrician technician, and the frac operator. The remaining tasks (blender operator, chemical operator, mechanic, float, pump walker, ground boss, safety, sand operator, sand pusher) had exposures at the ear that exceeded the TLV with the current hearing protection; with additional hearing protection, all job tasks (except the ground boss and mechanic) had estimated exposures at the ear below the TLV. For the ground boss and the mechanic, hearing protection alone will not lower their at-ear exposures below the TLV; other hierarchy of controls should be considered to lower exposure.

Action Level (AL) for HCP

The oil and gas extraction sector are exempt from the OSHA AL [29 CFR 1910.95(c)], which if exceeded, requires enrollment into a hearing conservation program (HCP). If the OSHA AL is exceeded, enrollment in an HCP is encouraged to protect worker health, reduce worker absenteeism, and other benefits (Chan, n.d.). According to the noise dosimetry results, the job tasks that exceeded the OSHA AL for the quiet fleet included the blender operator, crew lead, float, ground boss, ground walker, pump walker, sand pusher, and mechanic. The current hearing protection (NRR = 23) with a 50% correctional factor brings this estimated at-ear exposure below the AL of 85 dBA for all job tasks except for the mechanic and the sand pusher. For these employees' at-ear exposures to be below the 85 dBA 8-hr TWA with a 50% correctional factor, the workers should wear dual hearing protection (headset + earplugs) with earplugs that have a NRR of 29. For the conventional fleet, all job tasks exceeded the OSHA AL except for the electrician technician. With the current hearing protection (NRR = 23), the estimated at-ear exposure is below 85 dBA for all job tasks except for three: the mechanic, ground boss, and the chemical operator. With the dual hearing protection of earplugs (minimum 29 NRR) and headsets with a 50% correctional factor, the estimated at-ear exposure level is decreased below the OSHA AL.

Recommendation Summary

The quiet fleet horsepower pump controls worked well to reduce noise levels and worker exposure. Based on the results in the current study, oil and gas operators should consider replacing conventional pumps with quiet ones when possible. Current hearing protection devices (i.e., headsets with NRR = 23) work well but dual hearing protection is needed for the conventional fleet ground boss job task to be in compliance with 29 CFR 1910.95(b)(1). Further, based on observations of worker HPD use, HPD training should be provided to ensure that workers understand how to wear their hearing protection correctly.

Table 7. Quiet fleet noise reduction rating (NRR) of current HPD and dual hearing protection. *Red = over criteria, Green = below criteria*

	Task Evaluated	OSHA AL (85 dBA)			OSHA PEL (90 dBA)			ACGIH TLV (85 dBA)		
		Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor	Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor	Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor
		dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 29)	dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 29)	dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 33)
Quiet Fleet	Blender operator	90.9	82.9	-	88.7	80.7	-	91.2	83.2	-
	Chemical operator	88.8	80.8	-	86.2	78.2	-	90.7	82.7	-
	Crew lead	87.6	79.6	-	83.1	75.1	-	90.9	82.9	-
	Electrician technician	74.3	66.3	-	68.3	60.3	-	81.1	73.1	-
	Float	88.1	80.1	-	86.0	78	-	90.7	82.7	-
	Ground boss	86.9	78.9	-	83.4	75.4	-	89.8	81.8	-
	Ground walker	87.2	79.2	-	84.5	76.5	-	90.9	82.9	-
	Hydro operator	80.8	72.8	-	72.5	64.5	-	85.0	77.0	-
	Mechanic	92.6	84.6	76.6	91.9	83.9	-	100.0	92.0	82.0
	Pump walker	89.7	81.7	-	87.6	79.6	-	94.1	86.1	76.1
	Pump down	73.4	65.4	-	67.8	59.8	-	80.4	72.4	-
	Sand operator	77.1	69.1	-	74.1	66.1	-	83.6	75.6	-
	Sand pusher	93.2	85.2	77.2	91.7	83.7	-	96.0	88.0	78.0
	All tasks	86.6	78.6	-	83.0	75.0	-	90.5	82.5	-

Table 8. Conventional fleet noise reduction rating (NRR) of current HPD and dual hearing protection. *Red = over criteria, Green = below criteria*

	Task Evaluated	OSHA AL (85 dBA)			OSHA PEL (90 dBA)			ACGIH TLV (85 dBA)		
		Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor	Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor	Mean 8-hr TWA	Current HPD Protection Level with OSHA 50% correctional factor	Dual Hearing Protection Level with OSHA 50% correctional factor
		dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 29)	dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 29)	dBA	Headset (NNR = 23)	Headset + Earplug (NRR = 33)
Conventional Fleet	Blender operator	91.3	83.3	-	89.5	81.5	-	93.6	85.6	75.6
	Chemical operator	92.6	84.6	76.6	91.6	83.6	-	97.5	89.5	79.5
	Crew leader	85.4	77.4	-	84.0	76.0	-	92.2	84.2	-
	Electrician technician	78.1	70.1	-	76.0	68.0	-	89.8	81.8	-
	Float	90.1	82.1	-	88.3	80.3	-	93.3	85.3	75.3
	Frac operator	88.7	80.7	-	83.2	75.2	-	90.0	82.0	-
	Ground Boss	99.3	91.3	83.3	99.0	91.0	83.0	103.5	95.5	85.5
	Mechanic	96.1	88.1	80.1	95.8	87.8	-	104.5	96.5	86.5
	Pump walker	92.0	84.0	-	90.9	82.9	-	96.5	88.5	78.5
	Safety	90.7	82.7	-	89.8	81.8	-	97.2	89.2	79.2
	Sand operator	90.7	82.7	-	89.0	81.0	-	92.8	84.8	
	Sand pusher	92.0	84.0	76.0	88.9	80.9	-	93.7	85.7	75.7
	All tasks	91.2	83.2	75.2	89.8	81.8	-	95.6	87.6	77.6

CHAPTER 3: SUMMARY

Contribution to the Field

This study was the first, to the author's knowledge, to measure personal noise exposures of workers in the OGE sector, allowing the researchers objective data of noise exposures of hydraulic fracturing workers. This is also the first study in OGE to assess TTS in OGE employees.

This study was performed to address the hypotheses for the following three specific aims: (1) Determine personal noise exposures for oil and gas employees, (2) Characterize noise emissions from oil and gas operations and equipment, and (3) Determine if oil and gas employees suffer from temporary threshold shifts in hearing.

Specific Aim 1 – Determine personal noise exposures for oil and gas employees.

Alternative Hypothesis (HA) 1: Hydraulic fracturing employees are exposed to worksite noise exceeding published occupational exposure limits.

Null Hypothesis (H0) 1: Hydraulic fracturing employees are not exposed to worksite noise exceeding published occupational exposure limits.

HA 2: Conventional fracturing employees' personal noise exposures are significantly greater than quiet fracturing employees' personal noise exposures.

H0 2: There is no significant difference between quiet and conventional fracturing employees' personal noise exposures.

Specific Aim 1 was to determine personal noise exposures for oil and gas extraction workers. For Hypothesis 1, the null hypothesis was rejected, and the alternate hypothesis was accepted. That is, hydraulic fracturing workers were exposed to noise levels that exceeded published occupational exposure limits. Based on the personal noise dosimetry results, 42/50 (84%) of the quiet fleet and 34/34 (100%) of the conventional fleet workers sampled were at or over 100% noise dose according to the ACGIH TLV. Based on the OSHA PEL noise criteria, 9/50 (18%) of the quiet fleet workers and 15/34 (44.1%) of the conventional fleet workers were at or over 100% noise dose. For the OSHA AL criteria, 36/50 (72.0%) of the quiet fleet workers and 31/34 (91.2%) of the conventional fleet workers were at or over 100% noise dose. Likewise, for Hypothesis 2, the null hypothesis was rejected, and the alternate hypothesis was accepted. The conventional fleet personal noise exposures were significantly greater at all three criterion (OSHA AL p-value = 0.007, OSHA PEL p-value = 0.002, ACGIH TLV p-value = 0.001) when compared to the quiet fleet personal noise exposures.

<u>Specific Aim 2 – Characterize noise emissions from oil and gas operations and equipment.</u>

HA 3: Oil and gas extraction equipment noise is greater than or equal to 85 dBA at 1 meter distance or worker location.

H0 3: Oil and gas extraction equipment noise is less than or equal to 84 dBA at 1 meter distance or worker location.

Specific Aim 2 was to characterize noise emissions from oil and gas equipment. At both the quiet and conventional fracturing fleets, there were equipment or worker locations measured that equaled or exceeded 85 dBA. Therefore, for Hypothesis 3, the null hypothesis was rejected, and the alternative hypothesis accepted.

Specific Aim 3 – Determine if oil and gas employees suffer from temporary threshold shifts in hearing.

HA 4: Quiet and conventional fracturing employees experience a 10 dB shift or greater in hearing acuity at any frequency.

H0 4: Quiet and conventional fracturing employees do not experience a 10 dB shift in hearing acuity at any frequency.

HA 5: Conventional fracturing employees experience more 10 dB shifts or greater in hearing acuity at any frequency than the quiet fleet.

H0 5: There is no difference of hearing acuity in 10 dB shifts or greater in hearing acuity at any frequency between the quiet and conventional fleets.

Specific Aim 3 was to determine if oil and gas employees suffer from temporary threshold shifts in hearing. For Hypothesis 4, the null hypothesis was rejected, and the alternative hypothesis was accepted. Fracturing employees experienced a 10 dB shift or greater in hearing acuity at several frequencies. The quiet fleet fracturing workers experienced the highest proportion of shifts in the right ear at the frequencies 6000 Hz (7/35) and 8000 Hz (27/35). Conventional fracturing employees experienced the highest proportion of shifts in the right ear at 6000 Hz (4/35) and in the left ear at 500 Hz (6/35) and 8000 Hz (4/35). Hypothesis 5 failed to reject the null hypothesis. A mixed logistic regression comparing the conventional fleet to the quiet fleet at each frequency tested and ear type (R = right, L = left) suggest that there was no significant difference between fleet type and TTS at any frequency for either ear (p-values: R500 = 0.691, R1000 = 1.000, R2000 = 1.000, R3000 = 0.563, R4000 = 0.705, R6000 = 0.355, R8000 = 0.092; L500 = 0.709, L1000 = 0.645, L2000 = 1.000, L3000 = 0.563, L4000 = 1.000, L6000 = 0.987, L8000 = 1.000).

Conclusions

This study addresses a significant gap in research pertaining to noise and hearing status in the OGE sector, specifically hydraulic fracturing. This study compared the noise levels and the presence of TTS between the quiet and conventional fleets to evaluate the effectiveness of the engineering controls of the quiet fleet in protecting worker health. While these controls reduced the occupational exposure levels of the quiet fleet workers significantly more than the conventional fleet (OSHA AL p-value = 0.007, OSHA PEL p-value = 0.002, ACGIH TLV p-value = 0.001), hazardous noise levels still remained present in the “quiet” fleet. In both fleets workers experienced TTS, but no significant difference was observed between the type of fleet and presence of TTS. In both fleets, most equipment exceeded 85 decibels; a notable difference was that the pumps of the quiet fleet were ~14 dB lower than those of the conventional fleet. As both fleet employees experienced hazardous noise, the proper use and training for HPDs are necessary but are not currently mandated by the OSHA noise standard due to exemptions.

Although this study offers foundational information, further research is needed. More studies with larger sample sizes and more fracturing sites would provide additional data to determine if these exposures are representative for these populations of workers. Another factor to consider is the suspected exposure of these workers to onsite ototoxicants, which presents an additional concern; the synergistic effects of such chemicals, in conjunction with noise, could amplify hearing damage. A comprehensive approach to address these combined potential risks is crucial for ensuring OGE worker health.

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APPENDIX A: AUDIOMETRIC QUESTIONAIRE

Audiometric History

Participant Identifier: ________________

Date_________________________

Loud Noise Exposure within the last 2 days (48 hours)

Source(s): ____

Duration of exposure: ___________ Days ________________ Hours

Other Personal Noise Exposures: (check all that apply)

[ ] Loud music Hearing protection used? ___Yes ___No

[ ] Firearms Hearing protection used? ___Yes ___No

[ ] Power tools Hearing protection used? ___Yes ___No

[ ] Heavy machinery Hearing protection used? ___Yes ___No

[ ] Motorcycles

History (check all that apply):

[ ] Use of analgesics within last 7 days

- [ ] Acetaminophen (ex: Tylenol®) Frequency: __________days per week
- [ ] Ibuprofen (ex: Advil®, Motrin®) Frequency: __________days per week
- [ ] Aspirin (ex: Bayer®) Frequency: __________days per week
- [ ] Naproxen (ex: Aleve®) Frequency: __________days per week

[ ] Prior military service

[ ] History of hearing loss

[ ] Family history of hearing loss

[ ] History of recurrent ear infections

[ ] Current cold, flu or allergy symptoms

[ ] Current smoking

[ ] History of hearing aid R [ ] L [ ]

[ ] History of ringing ears

[ ] History of recurrent impacted ear wax

[ ] History of head injury

Hearing protection used at work (Type/Brand)______________________________________

Comments:____

TO BE COMPLETED BY TECHNICIAN

Dosimeter S/N____________________

Audiometer S/N____________________

Pre-Shift Audiogram Results

Right Ear			Left Ear	
Frequency (Hz)	Decibels (dB)		Frequency (Hz)	Decibels (dB)
500			500	
1000			1000	
2000			2000	
3000			3000	
4000			4000	
6000			6000	
8000			8000	

Comments:____

Physical exam of
ears: Left_______________________________________Right____________________________

Post-Shift Audiogram Results

Right Ear			Left Ear	
Frequency (Hz)	Decibels (dB)		Frequency (Hz)	Decibels (dB)
500			500	
1000			1000	
2000			2000	
3000			3000	
4000			4000	
6000			6000	
8000			8000	

Assessment: (check one)

[ ] Normal audiogram

[ ] TTS (≥ 5 dB loss) or other significant change (Right / Left)

Comments____

APPENDIX B: MAXIMUM ALLOWABLE OCTAVE-BAND SOUND PRESSURE LEVELS FOR AUDIOMETRIC TEST ROOMS

Figure A. OSHA Table D-1

Table D-1 - Maximum Allowable Octave-Band Sound Pressure Levels for Audiometric Test Rooms

Octave-band center frequency (Hz)	500	1000	2000	4000	8000
Sound pressure level (dB)	40	40	47	57	62

Source: OSHA. 1910.95 Appendix D - Audiometric Test Rooms | Occupational Safety and Health Administration. (n.d.). https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95AppD

Figure B. Occupational Noise Exposure for Railroad Operating Employees Table D-1

TABLE D–1.—MAXIMUM ALLOWABLE OCTAVE-BAND SOUND PRESSURE LEVELS FOR AUDIOMETRIC TEST ROOMS

Octave-band center frequency (Hz)	500	1000	2000	4000	8000
Sound pressure levels—supra-aural earphones	40	40	47	57	62
Sound pressure levels—insert earphones	50	47	49	50	56

Source: Occupational Noise Exposure for Railroad Operating Employees. (n.d.). https://www.govinfo.gov/content/pkg/FR-2006-10-27/pdf/06-8612.pdf

Figure C. ANSI S3.1-1999 (R2018) Maximum Permissible Ambient Noise Levels (MPANLs)

TABLE 2. Octave band ears covered maximum permissible ambient noise levels for three test frequency ranges as specified in ANSI S3.1-1999 when ears covered testing is done using a supra-aural or insert earphone

Octave Band Intervals	Supra-aural Earphone			Insert Earphone		
	125 to 8000 Hz	250 to 8000 Hz	500 to 8000 Hz	125 to 8000 Hz	250 to 8000 Hz	500 to 8000 Hz
125	35.0	39.0	49.0	59.0	67.0	78.0
250	25.0	25.0	35.0	53.0	53.0	64.0
500	21.0	21.0	21.0	50.0	50.0	50.0
1000	26.0	26.0	26.0	47.0	47.0	47.0
2000	34.0	34.0	34.0	49.0	49.0	49.0
4000	37.0	37.0	37.0	50.0	50.0	50.0
8000	37.0	37.0	37.0	56.0	56.0	56.0

Note: Values are in dB re: 20 μPa to nearest 0.5 dB and have been reprinted by permission of the Acoustical Society of America, New York, New York, U.S.A.

Source: Frank, T. (2000). ANSI Update: Maximum Permissible Ambient Noise Levels for Audiometric Test Rooms. American Journal of Audiology, 9(1), 3–8. https://doi-org.ezproxy2.library.colostate.edu/10.1044/1059-0889(2000/003)

APPENDIX C: SUPPLEMENTARY MATERIAL FOR "OCCUPATIONAL NOISE EXPOSURE AND HEARING ASSESSMENT OF HYDRAULIC FRACTURING WORKERS"

Table S1. Number and percentage of employees that had temporary threshold shifts (TTS) and hearing recovery at different frequencies. .

Fleet	Frequency (Hz)	Right ear TTS Number (%)	Left ear TTS Number (%)	Right ear Recovery Number (%)	Left ear Recovery Number (%)
Quiet (35 employees)	500	4 (11.4)	2 (5.2)	5 (14.3)	2 (5.7)
	1000	0 (0)	3 (8.6)	0 (0)	0 (0)
	2000	0 (0)	0 (0)	1 (2.9)	0 (0)
	3000	1 (2.8)	1 (2.8)	0 (0)	0 (0)
	4000	4 (11.4)	0 (0)	2 (5.7)	0 (0)
	6000	7 (20.0)	8 (22.9)	4 (11.4)	6 (17.1)
	8000	7 (20.0)	4 (11.4)	3 (8.6)	1 (2.9)
Conventional (35 employees)	500	3 (8.6)	6 (17.1)	4 (11.4)	1 (2.9)
	1000	2 (5.7)	2 (5.7)	1 (2.9)	2 (5.7)
	2000	3 (8.6)	1 (2.8)	1 (2.9)	1 (2.9)
	3000	2 (5.7)	2 (5.7)	1 (2.9)	3 (8.6)
	4000	1 (2.9)	1 (2.8)	0 (0)	1 (2.9)
	6000	4 (11.8)	0 (0)	0 (0)	2 (5.7)
	8000	2 (5.7)	4 (11.4)	2 (5.7)	2 (5.7)

Table S2. Results of mixed logistic regression analysis for TTS and hearing recovery comparing the conventional versus the quiet and fleets. No significance (p-value < 0.05) found in relationship between fleets and TTS or recovery. Odds ratios are also presented.

	TTS (≥ 10 dB)				Hearing Recovery (≤ −10 dB)			
Hz	**Right Ear p-value**	**Right Ear OR (95%)**	**Left Ear p-value**	**Left Ear OR (95%)**	**Right Ear p-value**	**Right Ear OR (95%)**	**Left Ear p-value**	**Left Ear OR (95%)**
500	0.691	0.727 (0.15, 3.51)	0.709	3.69 (0.004, 3500)	0.722	0.774 (0.19, 3.16)	0.927	0.639 (4.68e-05, 8727)
1000	1.000	5.36e+14 (2.22e-16, Inf)	0.645	0.646 (0.101, 4.13)	1.000	1.32e+14 (2.22e-16, Inf)	1.000	4.06e+14 (2.22e-16, Inf)
2000	1.000	5.38e+14 (2.22e-16, Inf)	1.000	Inf (2.22e-16, Inf)	1.000	1.000 (0.060, 16.6)	1.000	Inf (2.22e-16, Inf)
3000	0.563	2.06 (0.178, 23.8)	0563	2.06 (0.178, 23.8)	1.000	Inf (2.22e-16, Inf)	1.000	5.33e+14 (2.22e-16, Inf)
4000	0.705	0.203 (5.26e-05, 782)	1.000	9.7e+14 (2.22e-16, Inf)	1.000	2.22e-16 (2.22e-16, Inf)	1.000	Inf (2.22e-16, Inf)
6000	0.355	0.533 (0.141, 2.02)	0.987	3.85e-09 (2.22e-16, Inf)	1.000	2.22e-16 (2.22e-16, Inf)	0.727	0.383 (0.002, 83.7)
8000	0.092	0.242 (0.047, 1.26)	1.000	1.000 (0.229, 4.36)	0.645	0.646 (0.101, 4.13)	0.563	2.06 (0.178, 23.8)

TTS = Temporary threshold shift, Hz = Hertz, dB = Decibel, OR = Estimated odds ratio