Evaluation of Low-Frequency Noise, Infrasound, and Health Symptoms at an Administrative Building and Men's Shelter: A Case Study

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ABSTRACT

Responses to complaints about low-frequency noise and infrasound at workplaces have not been extensively documented in the literature. The National Institute for Occupational Safety and Health evaluated low-frequency noise, infrasound, and health symptoms among employees of an organization providing services to homeless persons. The organization's campus was evacuated after two loud noise and vibration incidents related to methane flare on an adjacent landfill. Employees were interviewed about health symptoms, perceptions of noise, and how the incidents were handled. Available medical records were reviewed. Sound level and noise frequency measurements taken in vacated campus buildings not during these incidents revealed overall levels across frequencies up to 100 hertz were 64 to 73 dB, well below those associated with adverse health effects. However, an unbalanced frequency spectrum could have contributed to the unusual sounds or vibrations reported before the first incident. Some symptoms predating the incidents are consistent with low-frequency noise exposure but are also common and nonspecific. Most interviewed employees (57%) reported being uncomfortable retur-

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ning to work on the campus. Multiple factors such as noise characteristics, health effects, and employee perceptions need to be considered when assessing health concerns related to low-frequency noise and infrasound.

KEYWORDS: noise, octave band analysis, auditory symptoms, vestibular symptoms, psychological contract, risk perception

Low-frequency noise (usually defined as sound in frequencies below 200 hertz [Hz]) and infrasound (sound in frequencies below 20 Hz) are ubiquitous and rarely, if ever, present without sound in higher frequencies.[1,2] Infrasound is generated naturally in the environment from sources such as ocean waves, waterfalls, thunder, and wind. For example, infrasound levels of up to 110 decibels (dB) have been measured at wind speeds of approximately 16 miles per hour.[1] Man-made sources such as air conditioners, fans, compressors, wind turbines, large engines, aircraft, and trains also generate low-frequency noise and infrasound. No studies have specifically focused on low-frequency noise and infrasound generated by landfill gas flares and people living or working near them.[3]

Studies have shown noise-related annoyance as one of the main effects from exposure to low-frequency sound and infrasound.[4–11] In addition, some case reports have reported subjective symptoms such as headaches, feelings of pressure in the head or ears, body vibration, concentration difficulties, or fatigue associated with infrasound and low-frequency noise.[12] Some researchers have reported that high sound levels in the frequencies of 30 to 80 Hz[2,13] or 25 to 63 Hz[12] may have a greater influence on annoyance than high levels of infrasound or sound at higher frequencies. A systematic review and evaluation of observational studies of an adult population living near a source of low-frequency noise and infrasound suggested an association between self-reported annoyance and symptoms such as sleep-related problems, difficulty concentrating, and headaches.[14] In a simulated office work environment, annoyance was correlated with subjective estimation of symptoms such as tiredness, dizziness, poor concentration, and sensation of pressure on the head when low-frequency noise conditions were produced.[15] However, few studies have evaluated the impact of low-frequency noise or infrasound on health effects or concerns in actual work environments.

In June 2019, the National Institute for Occupational Safety and Health (NIOSH) conducted an on-site Health Hazard Evaluation (HHE) at the campus of a nonprofit organization that provides services to homeless persons. HHEs are considered public health practice to assist workplaces in recognizing and controlling health hazards, not research studies. Employer representatives of the nonprofit organization and a mobile health services provider (mobile clinic) that served the men's shelter as well as county health department officials requested the HHE due to employees' concerns about low-frequency noise, infrasound, and health symptoms among staff who worked at the nonprofit organization's campus following two loud noise and vibration incidents. The campus was located next to a closed landfill (i.e., no longer accepting waste) with two methane flares and three motor-operated blowers (Fig. 1). The landfill and campus were owned by the county. The two methane flares were tall cylindrical stacks approximately 40 ft in height and 6 ft in diameter. To burn off methane, burners inside each flare burned the methane gas that was pulled from the landfill via underground pipes by nearby blowers. Air needed for methane combustion was supplied through three automated air louvers on the lower perimeter of the flares. The louver openings automatically adjusted air flow to keep the temperature at the burners at 1,650 degrees Fahrenheit. Typically, one flare and one blower were operated at a time, but this could be adjusted if needed to burn more methane. The methane-burning system was computer-controlled. Rapidly changing environmental conditions, such as heavy rainfall, could temporarily change the amount of methane generated in the landfill resulting in an imbalance in the air-to-methane ratio, leading to more combustion-related noise from combustion instability and combustion roar. On February 4, 2019 (first incident), employees reported unusually loud noise and strong vibrations in the administrative building

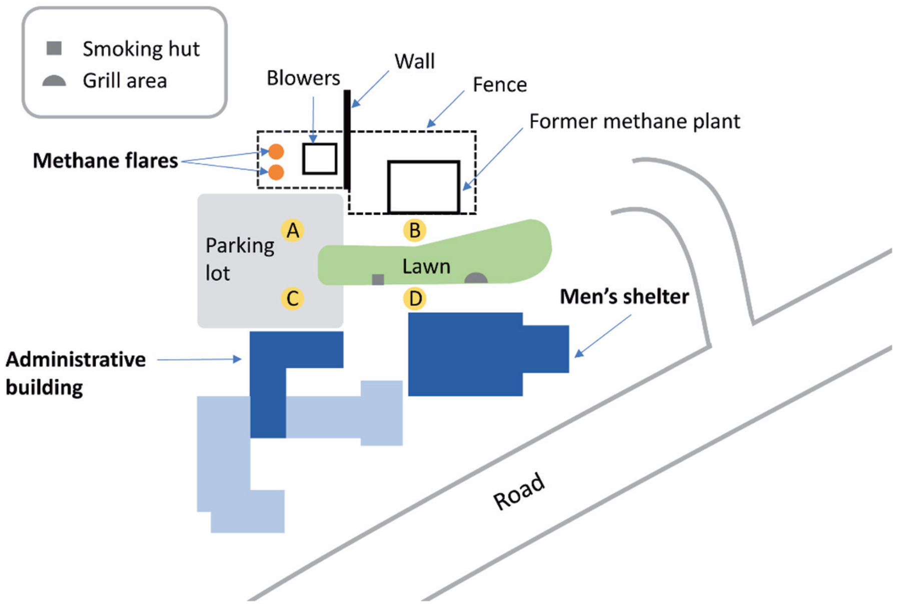

Figure 1 Schematic of the campus and methane flares. Not drawn to scale. Employees worked in the administrative building or the men's shelter. Circles with A–D refer to parking lot locations where we made noise measurements. The closed landfill extends from the top edge of the fenced area to beyond the top of the diagram.

on campus coming from the direction of the methane flares. During the loud noise and vibration incident, some employees reported psychological discomfort and physical symptoms such as vertigo, dizziness, and ear pressure. Employees from the administrative building were relocated to an off-campus building within 1 week. On May 17, 2019 (second incident), loud noise and vibrations were reported at the men's shelter on campus. After some employees and shelter clients reported not feeling well during or soon after the incident, the men's shelter staff and clients were relocated to an off-campus site, thus vacating the entire campus. Employees expressed concerns about how the situation was being handled, for example, regarding the safety of the site and initial evacuation of only the administrative building following the first loud noise and vibration incident. The objective of this evaluation was to characterize low-frequency sounds by evaluating one-third octave band noise frequency levels, health symptoms among employees, and employee perceptions of how the loud noise and vibration situation was handled by the nonprofit organization and the county in this unique work environment.

MATERIALS AND METHODS

In this descriptive study, we assessed noise levels at the vacated campus, employee health, and employee perceptions of how the loud noise and vibration situation was handled based on noise measurements, confidential semistructured interviews, and medical record review.

Noise Assessment

SOUND LEVEL AND ONE-THIRD OCTAVE BAND MEASUREMENTS

We used an integrating sound level meter and sound frequency analyzer (Larson Davis, Model 831) equipped with a 1.3-cm (½ in) random incidence microphone (Larson Davis, Model 377B20) for measurements. The sound level meter and microphone met American National Standards Institute (ANSI) S1.4 2014 Type 1 standards and the octave band frequency filter met ANSI S1.11-2004 Class 1 standards. The instrument was sampled at a rate of 51,200 Hz (i.e., 51,200 measurements per second) and was set up to integrate using linear averaging at 1-second time history intervals. We measured one-third octave band noise frequency levels using a slow weighting (1,000 msec) time constant and the Z-weighting (flat or unweighted) response at each one-third octave band center frequency from 6.3 to 20,000 Hz, which corresponds to frequencies of 5.62 to 22,400 Hz. The instrument also simultaneously measured sound levels using A-weighting (dBA) and C-weighting (dBC). We calibrated the instrument and microphone before and after each of the 2 days of measurements using a sound level calibrator (Larson Davis, CAL200).

During measurements, the instrument was either hand-held or mounted on a tripod at a height of approximately 1.5 m (5 ft) above floor or ground level. We took measurements within rooms inside the administrative building and the men's shelter and at six locations between the flare areas and the administrative building and men's shelters, identified as Locations A–D, grill area, and smoking hut in Fig. 1. The administrative building was located about 46 m (150 ft) from the flares and the men's shelter was located about 69 m (225 ft) from the flares. We also took measurements offsite along the city road behind the administrative building and men's shelter. At each location, most measurements were taken for a duration of approximately 30 to 45 seconds, resulting in a standard deviation for these averaging times ranging from 0.54 to 0.65 dB. The flares were fully operational during our site visit. Only one flare operated at a time, as was normal procedure. On one of the days of our site visit, we took measurements when the flares were running and when they were turned off, as the flares were shut down for a few hours for operational adjustments. During the maintenance shutdown, we took one-third octave band measurements within eight different rooms in the administrative building for comparison to levels when a flare was operating. All the rooms had exterior windows, with five rooms facing toward the flares. The other three rooms had windows facing out toward a side or toward the rear (roadside) of the building.

ASSESSMENT OF EMPLOYEE PERCEPTIONS OF NOISE

Employee perceptions of noise were ascertained through confidential, semistructured interviews. All 45 current or former employees of the nonprofit organization who (1) had been working during the February 2019 incident, May 2019 incident, or both and (2) were available during our site visit were invited for confidential interviews. We also invited all three mobile clinic employees who provided services at the men's shelter on a rotating schedule. Clients of the nonprofit organization were not employees and not within the scope of the NIOSH HHE program to evaluate. Our convenience sample was interviewed in person or by telephone. Reponses were recorded on a preprinted interview form by the interviewer.

During the interviews, we asked employees whether they had heard any unusual sounds or experienced any unusual vibrations since starting to work on the campus. If an employee responded "yes," we asked about when they first heard unusual sounds or felt unusual vibrations by building. We also asked employees to describe unusual sounds and vibrations. We grouped descriptions of unusual sounds and vibrations together for analysis.

During the interviews, we also discussed work characteristics and demographic information. Employees were classified as administrative building or men's shelter employees based on their self-reported primary work area before the relocations. Mobile clinic employees were classified as men's shelter employees.

Employee Health Assessment

Employee health assessment was based on interviews and medical record review. During interviews, we asked employees about symptoms and medical care sought for symptoms that they thought were related to unusual sounds or vibrations. If an employee reported seeking medical care for symptoms, we attempted to obtain and review relevant medical records.

We grouped tinnitus, ear pain, ear pressure, and hearing loss as auditory symptoms. We grouped vertigo and balance problems as vestibular symptoms.[16–18] Auditory or vestibular symptoms were considered to have a plausible (i.e., possible and medically reasonable) alternative explanation if an employee reported (1) having a history of that symptom, (2) having a medical condition for which that symptom is characteristic, (3) taking an over-the-counter or prescription medication known to induce the symptom, or (4) based on medical record review, if available.

Employee Perceptions of How the Loud Noise and Vibration Situation Was Handled

During interviews, we asked employees about their perceptions and experience of the loud noise and vibration incidents that led to their workplace being evacuated/relocated. Employees were asked each question twice, once focusing on the nonprofit organization, and once focusing on the county. These questions included, "Do you have any concerns about how the situation was handled by the nonprofit organization/the county," "Are you satisfied with the nonprofit organization/the county's communication to employees about the situation," and "Do you trust the nonprofit organization/the county to care for your health and safety at work?" Each response was recorded as yes, no, or unsure, and was followed by an open-ended question asking for an explanation of the response. We also asked employees if they were comfortable with returning to work at the vacated locations. If the response was "no" or "unsure," it was followed by an open-ended question: "what would be needed for you to feel comfortable returning to work [at the site]?"

Statistical Analysis

Descriptive analysis was performed on one-third octave band frequency data using Larson Davis G4 software and Microsoft Excel. One-third octave band measurements and overall sound levels were compared to occupational infrasound and low-frequency noise threshold limit values (TLVs) established by the American Conference of Governmental Industrial Hygienists (ACGIH).[19] The difference between overall C-weighted decibel (dBC) and A-weighted decibel (dBA) measurements within the administrative building and men's shelter (C–A difference) was calculated to assess annoyance. One-third octave band frequency levels in the administrative building when the flares were on versus off were compared to four different European guidelines suggested for assessing indoor low-frequency noise.[13,20,21]

Descriptive analysis of employee health and perceived noise or vibration characteristics was performed using R version 3.5.1. Fisher's exact test was used to compare proportions of employees who reported unusual sounds or vibrations and the prevalence of symptoms by whether employees primarily worked in rooms facing the flares or not. The exact binomial test was used to assess whether the percentage of administrative building and men's shelter employees with a given symptom were similar to the percentage of employees who primarily worked in those two areas. An alpha level of 0.05 was considered to indicate statistical significance.

Descriptive analysis of employee perceptions of how the loud noise and vibration situation was handled was performed using transcriptions of the employees' responses to interview questions in a Microsoft Excel spreadsheet. Open-ended responses were analyzed to identify common themes, which were then tallied to report the number of employees expressing similar concerns. Employees' responses were tallied into one or more themes. To protect employee confidentiality, we did not present results about a particular concern if it was reported by fewer than three employees.

RESULTS

Noise Assessment

NOISE SOUND LEVEL AND ONE-THIRD OCTAVE BAND MEASUREMENT

The primary external sources for noise near the administrative building and men's shelter were the operating methane flare(s) (Fig. 2) and blower(s). Fig. 3 shows the one-third octave band noise levels at an operating flare and at an operating blower. The highest sound levels in the vicinity (1–4 m [2–12 ft] from the flare) of the operating methane flare occurred in frequencies of 10 to 50 Hz and ranged from 70.8 to 101.2 dB, depending on frequency and distance from the flares. The highest sound levels (95.0–101.2 dB), measured approximately 1 m (2–3 ft)

Figure 2 Photograph of the methane flares at the time of the site visit. (Photo by NIOSH.)

away from an air intake louver of the flare stack, were at 20 Hz. At 12.5, 16, and 25 Hz, the levels ranged from 84.9 to 93.5 dB. At 3 m (10 ft) from a flare in operation, the sound level at 20 Hz was 91.2 dB, and at the adjacent one-third octave band frequencies of 12.5, 16, and 25 Hz, the sound levels were at or slightly above 80 dB. The highest sound levels generated by an

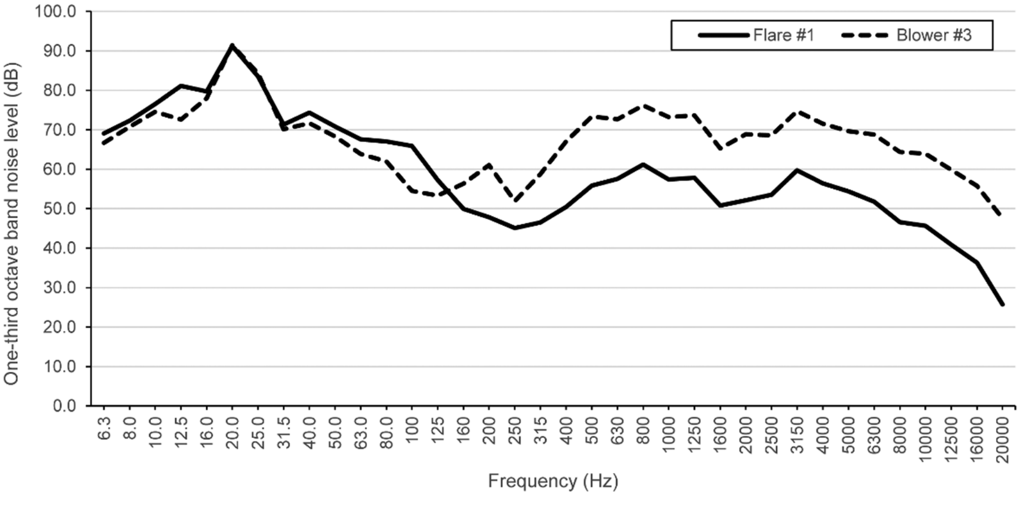

Figure 3 One-third octave band noise levels measured approximately 2.5 to 3 m (8–10 ft) from an operating methane flare and blower.

operating blower were in the frequencies from 500 to 6,300 Hz, ranging from 68.6 to 76.2 dB. The measurements near the blower also showed high sound levels in frequencies below 50 Hz, but these were due to the sound generated by the nearby operating methane flare.

One-third octave band sound levels were well below the ACGIH frequency-specific acoustic TLV of 145 dB and the overall TLV of 150 dB (**Appendix**), for infrasound and low-frequency sound between 1 and 100 Hz.[19] The highest one-third octave band levels we measured from 6.3 to 20,000 Hz at each location was at 20 Hz, except for measurements taken along the city road behind the administrative and men's shelter buildings, where the levels were highest at 63 Hz. One-third octave band noise levels at 20 Hz ranged from 60.5 to 71.4 dB in the administrative building, 60.4 to 65.6 dB in the men's shelter, and 75.8 to 84.9 dB at the four outdoor locations in the parking lot, grill area, and smoking hut.

Table 1 provides the overall dBC and dBA measurements and C–A differences within the administrative building and men's shelter. Overall C-weighted sound levels ranged from 55.9 to 67.2 dBC in the administrative building and from 58.7 to 62.4 dBC in the men's shelter. A-weighted sound levels ranged from 26.5 to 39.8 dBA in the administrative building and 42.6 to 48.0 dBA in the men's shelter.

Fig. 4 compares median one-third octave band frequency levels in the administrative building when the flares were on versus off. In eight sampled rooms with exterior windows in the administrative building, the highest one-third octave band noise levels when the flares were on occurred at 20 Hz, ranging from 62.1 to 71.4 dB. When the flares were off, the highest one-third octave band noise levels occurred at 8 Hz, ranging from 50.5 to 59.6 dB. Levels were slightly higher in the five rooms facing the flares across the frequencies of 10 to 100 Hz, but were slightly lower at all other frequencies (and nearly the same from 10,000 to 20,000 Hz). Across most frequencies, no substantial difference in one-third octave band levels within the administration building were identified when flares were on versus off. The greatest difference in one-third octave band noise levels between

Table 1 C-weighted and A-weighted sound level measurement results and their differences in the administrative and shelter buildings

Measurement location	C-weighted sound level (dBC)	A-weighted sound level (dBA)	dBC–dBA difference (dB)
Admin bldg. Room 100	60.4	27.1	33.3
Admin bldg. Room 101	67.2	28.8	38.4
Admin bldg. Room 102	60.7	26.5	34.2
Admin bldg. Room 103	63.1	39.8	23.3
Admin bldg. Room 105	64.6	30.5	34.1
Admin bldg. Room 108	63.7	28.3	35.4
Admin bldg. Room 109	59.9	29.0	30.9
Admin bldg. Room 110	59.7	37.7	22.0
Admin bldg. Room 113	55.9	39.2	16.7
Admin bldg. Room 117	57.3	36.1	21.2
Admin bldg. Room 118	59.1	31.3	27.8
Admin bldg. Room 121	60.8	31.8	29.0
Admin bldg. Room 123	59.8	34.6	25.2
Shelter bldg. Main room	62.4	42.6	19.8
Shelter bldg. Socializing room	58.7	43.8	14.9
Shelter bldg. Check-in desk	61.4	45.2	16.2
Shelter bldg. Office area	61.9	45.6	16.3
Shelter bldg. Intake office	60.2	48.0	12.2

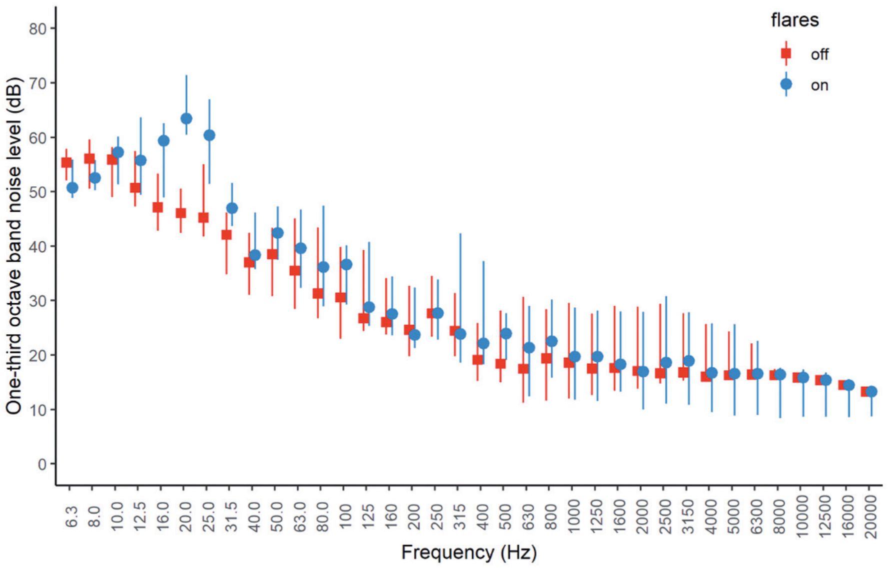

Figure 4 One-third octave band noise levels across eight rooms in the administrative building when a methane flare was on versus when the flare was off. The square or circle shows the median. The vertical line shows the range of noise levels.

flare on and flare off conditions occurred across the frequencies of 16, 20, and 25 Hz. The differences in the median dB levels at these three one-third octave band frequencies were 17.4 dB at 20 Hz, 15.2 dB at 25 Hz, and 12.2 dB at 16 Hz. At all other frequencies, the median differences between flare on and flare off conditions ranged from –4.6 to 6.1 dB, with a negative difference indicating that one-third octave band noise levels were higher when the flares were off. Because the building was unoccupied at the time of the evaluation, the heating, ventilation, and air conditioning system did not contribute to background noise during any of the measurements under flare on or flare off conditions.

Fig. 5 compares the median one-third octave band frequency levels in the administrative building when a flare was on and off to European guidelines suggested for assessing indoor low-frequency noise and infrasound.[13,20,21] When the flare was on, our measured levels exceeded the Polish guidelines at frequencies of 20 Hz, 25 Hz, and 50 to 250 Hz, and exceeded German and Dutch guidelines at frequencies of 50 to 100 Hz. The highest exceedance was at 250 Hz when compared to Polish guidelines and was at 100 Hz when compared to German and Dutch guidelines. None of the measured levels were above British guidelines. When the flare was off, we similarly found that levels were above German and Dutch guidelines from 63 to 100 Hz and above Polish guidelines from 100 to 250 Hz.

EMPLOYEE PERCEPTIONS OF NOISE

Of the 48 employees invited for interviews, 46 employees (96%) participated. Interviewed employees consisted of 44 nonprofit organization employees and 2 mobile clinic employees. The median job tenure was 3 years (range: 5 months to 14 years). Nonprofit organization employees worked for a median of 40 hours per week (range: 30–65 hours per week). Mobile clinic employees were on site 2 to 3 partial days per week. Based on the reported primary work area before the relocations, there were 29 (63%) administrative building employees and 17 (37%) men's shelter employees. Of the 46 interviewed employees, 30 (65%) were female. The median age was 44 years (range: 24–69 years).

Thirty-seven (80%) interviewed employees reported noticing either unusual sounds or vibrations during their work tenure at the site. Descriptions of the frequency, duration,

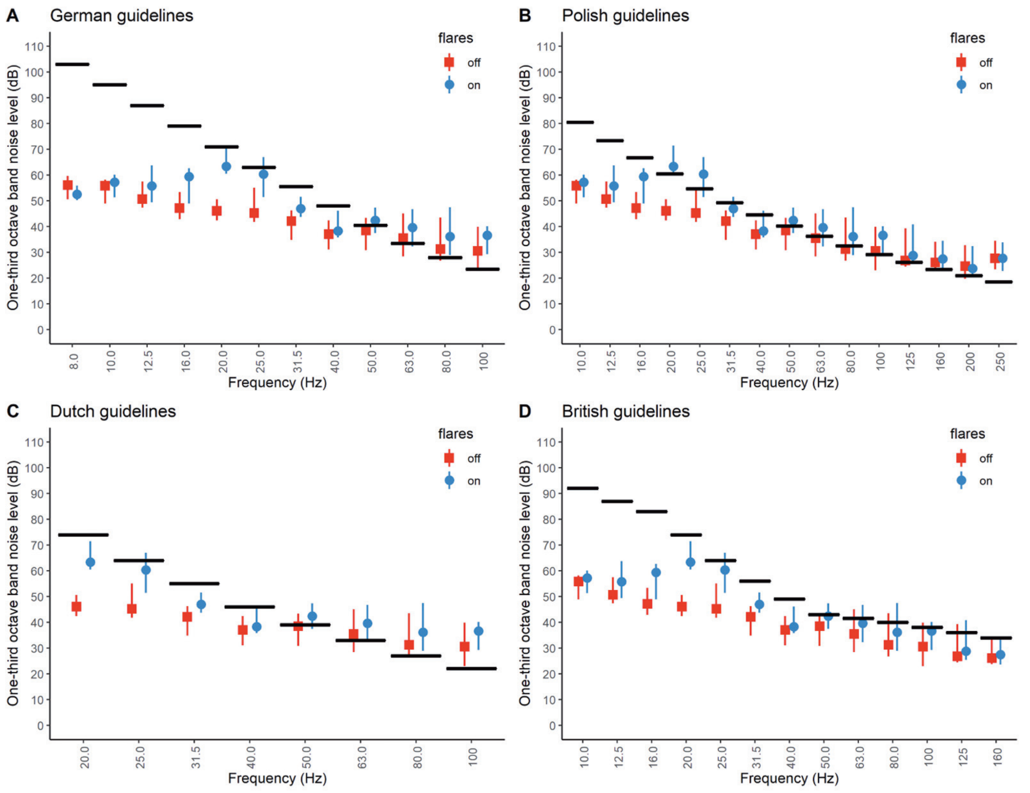

Figure 5 Comparison of median one-third octave band noise levels measured in the administrative building with a flare on versus off to European indoor guidelines for low-frequency noise and infrasound. Maximum noise levels by frequency are shown as horizontal black bars. Guidelines were not established for all frequencies measured. German guidelines (**A**) covered 8–100 Hz. Polish guidelines (**B**) covered 10–250 Hz. Dutch guidelines (**C**) covered 20–100 Hz. British guidelines (**D**) covered 10–160 Hz. The square or circle shows the median. The vertical line shows the range of noise levels.

and intensity of unusual sounds or vibrations varied. Some employees described a rumbling, analogous to a large truck driving by, or a jackhammer, that can be heard or felt prior to the incidents. Some employees described vibrating windows or objects or a sensation that the building was shaking.

Regarding the location of sounds or vibrations, 28 (61%) employees reported experiencing them in the administrative building and 11 (24%) employees reported experiencing them in the men's shelter. These numbers included 2 (4%) employees who reported experiencing unusual sounds or vibrations in both locations. The proportion of employees working primarily in rooms facing the flares who reported unusual sounds or vibrations was similar to the proportion of other interviewed employees who reported unusual sounds or vibrations ($p = 0.69$).

Regarding when unusual sounds or vibrations were first noticed, responses ranged from the beginning of employment to the day of each incident. Of the 28 employees who reported experiencing unusual sounds or vibrations in the administrative building, 25 (89%) reported that they noticed them occurring before the February 2019 incident. Of the 11 employees who reported experiencing unusual sounds or vibrations in the men's shelter, 3 (27%) reported that they noticed them occurring before the May 2019 incident.

Employee Health Assessment

Twenty-four (52%) employees responded "yes" or "unsure" when asked whether they experienced any symptoms that they thought were related to unusual sounds or vibrations at the

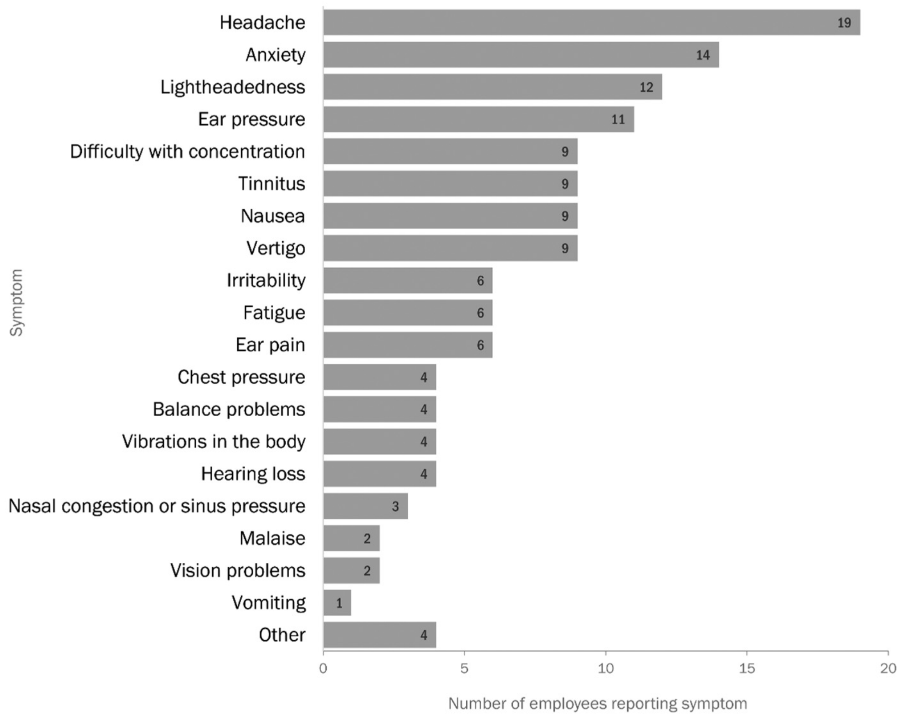

Figure 6 Number of employees reporting various symptoms related to unusual sounds or vibrations at work.

site. The most common symptom was headache ($n = 19$), followed by anxiety ($n = 14$), and lightheadedness ($n = 12$; Fig. 6). Six employees described one or more sources of their anxiety: uncertainty related to the incidents and subsequent relocation ($n = 4$), whether the campus was safe ($n = 2$), noise ($n = 1$), and methane gas ($n = 1$). Of the 46 interviewed employees, 14 (30%) reported auditory symptoms and 9 (20%) reported vestibular symptoms.

In general, information about symptom onset, duration, and timing relative to the incidents was incomplete. When responses about symptom onset were available, the percentage of employees who reported that symptoms occurred before the incident in their primary area ranged from 0% for ear pain, body vibrations, vision problems, and irritability to 44% for vertigo and 50% for hearing loss.

Of the 24 employees who reported symptoms that they thought were related to unusual sounds or vibrations at the site, 9 (38%) saw a health care provider. One employee reported being hospitalized. Of the nine employees who saw a health care provider, we reviewed the relevant medical records of five (56%) employees who agreed to making them available for review.

Some employees had plausible alternative explanations for auditory or vestibular symptoms. Of the 14 employees who reported auditory symptoms, 2 (14%) had a plausible alternative explanation for their auditory symptoms. Of the nine employees who reported vestibular symptoms, three (33%) had a plausible alternative explanation for their vestibular symptoms.

The proportion of employees working primarily in rooms facing the flares who reported symptoms was similar to the proportion of other interviewed employees who reported symptoms ($p = 0.21$). Similar results were obtained for auditory symptoms ($p = 0.60$) and vestibular symptoms ($p = 0.64$).

The 24 employees who reported symptoms that they thought were related to unusual sounds or vibrations consisted of 19 (79%) administrative building employees and 5

(21%) men's shelter employees. This breakdown was not statistically different from the proportion of administrative building employees (63%) and men's shelter employees (37%) interviewed ($p = 0.13$). Similar results were obtained when comparing the proportion of administrative building and men's shelter employees reporting each symptom individually.

Employee Perceptions of How the Loud Noise and Vibration Situation Was Handled

Table 2 shows the categorical responses to questions about employee perceptions of how the situation was handled by the nonprofit organization and the county. When asked if they had concerns about how the situation was handled by the nonprofit organization, 12 (26%) replied "yes." When interviewed employees were given the opportunity to explain their response, 25 employees provided more detail. Eight (32%) employees commented positively about how the nonprofit organization handled the situation. The most common concern ($n = 7$; 28%) was that the men's shelter was not evacuated until months after the administrative building was evacuated. When asked if they had concerns about how the situation was handled by the county, 27 (59%) employees replied "yes." When given the opportunity to explain their response, 32 employees provided more detail. The most common concerns included a perception that the county did not take the situation seriously ($n = 10$; 31%); a lack of communication about the situation ($n = 9$; 28%); and the length of time it took to evacuate the men's shelter ($n = 7$; 22%).

Most interviewed employees ($n = 35$; 76%) reported that they were satisfied with communication from the nonprofit organization. Twenty-eight employees provided more detail about their response, and a quarter of the responses ($n = 7$) were positive in nature. The most common concerns reported were being unsure of what plans were moving forward ($n = 6$; 21%); a perceived lack of transparency from the nonprofit organization ($n = 4$; 14%); wanting more information about how the situation was being assessed ($n = 3$; 11%); and a perception that the information was being shared informally (e.g., "office gossip"; $n = 3$; 11%). Most of the interviewed employees ($n = 28$; 61%) were not satisfied with communication from the county, and another 14 (30%) were unsure. Thirty-five employees provided more detail about their response, with the most common response ($n = 27$; 77%) being that there was no communication from the county. The next most frequent response ($n = 4$; 11%) was that the county was taking too long to share information.

Most of the interviewed employees ($n = 42$; 91%) reported that they trusted the nonprofit organization to care for their health and safety at work. Twenty-eight employees provided more detail about their response, with the most common responses ($n = 21$; 75%) being positive in nature (e.g., "they look out for us and are supportive"). One-third ($n = 15$; 33%) of the interviewed employees reported that they trusted the county to care for their safety and

Table 2 Employee perceptions of how the loud noise and vibration situation was handled by the nonprofit organization and the county ($n = 46$)

Question	Nonprofit organization number (%)			County number (%)		
	Unsure	Yes	No	Unsure	Yes	No
Do you have concerns about how the situation was handled by the ____?	3 (7)	12 (26)	31 (67)	7 (15)	27 (59)	12 (26)
Are you satisfied with ____'s communication to employees about the situation?	1 (2)	35 (76)	10 (22)	14 (30)	4 (9)	28 (61)
Do you trust _____ to care for your health and safety at work?	0 (0)	42 (91)	4 (9)	4 (9)	15 (33)	27 (59)

health, while another four (9%) said they were unsure. Thirty-two employees provided more detail about their response, with the most common responses being that nothing was being done because the situation was not being taken seriously ($n = 8$; 25%) and the perception that the county does not care about the non-profit organization ($n = 7$; 22%). Six (19%) of the comments were positive in nature.

When asked whether they would be comfortable returning to work at the vacated campus, 25 of 44 interviewed employees (57%) said "no," and 19 (43%) said "yes." Thirty-two employees provided a response when asked what it would take to make them comfortable enough to return, with the most common responses being that there is nothing that could be done to alleviate their concerns ($n = 12$; 38%); if testing is completed that shows the campus is objectively "safe" ($n = 9$; 28%); or if the problem is "fixed" ($n = 8$; 25%). Others mentioned they would be comfortable returning if the vibrations stopped ($n = 5$; 16%).

DISCUSSION

Noise Assessment

In this evaluation, we assessed sound levels in a workplace near a source of low-frequency noise and infrasound after two loud noise and vibration incidents. The predominant noise frequency (i.e., frequency at which the highest noise levels occurred) generated by an operating methane flare was at the one-third octave band center frequency of 20 Hz. The second highest noise levels were at the adjacent one-third octave band frequencies of 16 and 25 Hz. These results were similar to the predominant frequency (17 Hz) for combustion in methane flares reported in a guidance document on landfill gas flaring prepared for the Scottish Environmental Protection Agency.[3]

Our measurements, which did not reflect conditions during the reported loud noise and vibration incidents, were well below the ACGIH TLVs for infrasound and low-frequency noise. The ACGIH TLV of 145 dB for one-third octave band frequencies from 1 to 100 Hz and 150 dB for overall sound pressure levels averaged across frequencies from 1 to 100 Hz are the only U.S. occupational exposure limits established specifically for low-frequency noise and infrasound.[19] TLVs are recommended limits, not enforceable regulatory limits, established to protect employees against non-auditory effects related to comfort, performance, and health.[19] ACGIH also notes that exposure to low-frequency sounds, particularly across frequencies of 50 to 100 Hz, which are in the upper torso resonance range, can lead to discomfort and annoyance. ACGIH advises that if discomfort is experienced, levels may need to be reduced to a level at which the problems are alleviated.[19]

Similarly, our measurements were also well below levels reported in the research literature as likely to cause adverse health effects. An early study found that employees exposed for 15 minutes to simulated industrial infrasound at frequencies of 5 and 10 Hz and levels of 100 and 135 dB reported symptoms such as fatigue, ear pressure, poor concentration, drowsiness, and perception of vibration in internal organs.[22] Research has also reported that symptoms such as headache, sensation of body sway, fatigue, tinnitus, and respiratory difficulties following exposure to infrasound levels ranged from 100 to 120 dB.[23] In contrast, a study of 145 long-haul truck drivers exposed to infrasound of 115 dB did not find that reported symptoms such as fatigue, vertigo, tinnitus, hearing impairment, headache, abdominal symptoms, or hypertension were statistically significantly more common when analyzed with respect to exposure and hours of work, driving, and rest.[24] A randomized controlled trial of exposure to a device producing infrasound at 6 Hz at 80 to 90 dB or a sham device for 28 days did not find changes in vertigo, chest pain, nausea, respiratory symptoms, numbness or tingling, or self-reported mental health problems before or after exposure in either group.[25]

Our comparison of one-third octave band measurements when a flare was operating versus not operating showed the influence of noise generated by the flares within campus buildings. At 16 to 25 Hz, sound levels in the administrative building were 12 to 17 dB higher when the flares were operating compared to when the flares were not operating. The frequency-specific or overall sound levels we measured are not known to cause adverse health effects. However, complaints of annoyance due to low-frequency noise tend to be associated with an unbalanced noise spectrum,[11,26] which can occur when sound levels in the low frequencies are higher relative to the sound levels in the higher frequencies.

Noise-related annoyance is one of the main effects from exposure to infrasound.[4–11] Researchers have reported that high sound levels in the frequencies 30 to 80 Hz[2,13] or 25 to 63 Hz[12] may have a greater influence on annoyance than high levels of infrasound or at frequencies above these ranges. Persson Waye et al[15] reported that annoyance was correlated with subjective estimation of symptoms such as tiredness, dizziness, poor concentration, and sensation of pressure on the head when low-frequency noise conditions occurred in the workplace. A cross-sectional epidemiologic study assessing the health and well-being of Canadians living near wind turbines found that reported annoyance increased as noise levels outside residences exceeded 35 to 46 dBA. Participants also indicated similar annoyance to vibrations, flicker from blade rotation, warning lights on wind turbines, and visual appearance. The study authors did not find a relationship between wind turbine noise and reported health effects such as headaches, dizziness, sleep problems, and stress.[27] A recent review found an association between self-reported annoyance and wind turbine noise, which includes low-frequency noise and infrasound, while health effects were related to annoyance rather than exposure to low-frequency sound and infrasound directly.[10]

One method for assessing the potential for the likelihood of annoyance complaints due to low-frequency noise is a comparison of overall C-weighted to A-weighted sound pressure levels. C-weighting and A-weighting refer to different metrics for measuring and integrating noise across the frequency spectrum. Because humans do not perceive loudness equally across all frequencies and have diminished perception of loudness at low frequencies, A-weighted sound level measurements approximate equal loudness characteristics of human hearing for pure tones relative to a reference of 40 dB at 1,000 Hz.[28] C-weighting is a measure of noise across all frequencies, similar to linear weighting, except for slight attenuation at frequencies below 50 Hz and above 5,000 Hz. At frequencies above 500 Hz, A- and C-weighting are quite similar. Researchers have suggested that a C–A difference of 20 dB or more is indicative of an unbalanced noise spectrum and potential low-frequency noise problems and low-frequency noise annoyance complaints.[2,26] Kjellberg et al[29] measured noise levels and noise annoyance at a variety of workplaces (offices, laboratories, and industrial settings). Using regression analyses, the authors found that C–A differences may make a "significant, although small, contribution to the explanation of differences in annoyance ratings."[29] Downey and Parnell[30] argued that C–A differences might be useful as a screening tool for noise annoyance, but this method may not be appropriate in all settings, for example, when noise levels are low (below 40 dBA) or when measurements are made at large distances from the source.

C–A differences in the administrative building ranged from 17 to 38 dB (median: 29 dB). The C–A differences in the men's shelter ranged from 12 to 20 dB (median: 16 dB), indicating that annoyance may be more likely for administrative building compared with men's shelter occupants. During interviews, 89% of employees who reported experiencing unusual sounds or vibration in the administrative building stated they occurred before the February 2019 incident, whereas 27% of employees who reported experiencing unusual sounds or vibrations in the men's shelter stated they noticed them before the May 2019 incident. It is important to note that during our measurements the administrative and men's shelter buildings were unoccupied. If these buildings had been fully occupied, it is highly likely that the sound levels, particularly in frequencies above 500 Hz, would have been higher due to the occurrence of conversation (which is generally in the 500- to 2,000-Hz range) and other daily activities. This would likely have the effect of diminishing the C–A differences.

Our one-third octave band frequency measurements in the administrative building when a flare was on or off exceeded some European guidelines suggested for assessing indoor low-frequency noise and infrasound following complaints of annoyance. These findings provide additional support to the potential for annoyance from low-frequency noise. Interestingly, at some of the low frequencies above 63 Hz, we found that levels exceeded German, Dutch, and Polish guidelines, even when the flares were off. Contribution of low-frequency noise from nearby city traffic could be a factor in these results. While heating, ventilation, and air conditioning systems can contribute to low-frequency noise, the buildings were unoccupied during the measurements and these systems were off.

Employee Health Assessment

Approximately half of the employees we interviewed reported symptoms that they thought were related to unusual sounds or vibrations. It is likely that different subsets of employees have different explanations for their symptoms. First, some employees might have developed symptoms during or after the February and May 2019 incidents, which were described as loud sounds or intense vibrations. Auditory symptoms, such as hearing loss, ear pain, tinnitus, and ear pressure, can occur after exposure to loud noise, such as after a concert. Vestibular symptoms after exposure to low-frequency sound or infrasound are less commonly reported in the scientific literature. One study found exposure to noise at 5 and 16 Hz at 95 dB for 5 minutes affected body sway, suggesting that infrasound might affect inner ear function and balance.[31]

Some symptoms reported by interviewed employees as predating the incident in their primary area are consistent with symptoms reported in studies about background low-frequency noise, such as headache, fatigue, difficulties with concentration, vibrations in the body, and ear pressure in the absence of specific incidents.[4,8,12] However, many of these symptoms are also common, nonspecific, and might have multiple causes. Some employees with auditory or vestibular symptoms had a plausible alternative explanation for their symptoms based on their medical history. Most employees did not undergo medical evaluation and medical records for some evaluated employees were not available, which might have led to missed opportunities to identify plausible alternative explanations.

Employee Perceptions of How the Loud Noise and Vibration Situation Was Handled

Overall, the employee responses regarding their perceptions of how the situation was handled indicated that there were concerns about how the nonprofit and county would move forward. Although sound levels were well below occupational exposure limits, over half (57%) of the interviewed employees reported that they were uncomfortable with returning to work at the vacated campus. We recommended that these findings be taken into careful consideration by the nonprofit and county representatives when making decisions of whether to return to the vacated campus.

Having employees return to work at a location that they perceive as unsafe may represent a breach of psychological contract, or the implicit agreement that the employer will value and care for the worker in exchange for good work.[32,33] Breach in psychological contract often results in employees feeling violated, and it diminishes trust in an organization. Further, such breaches in psychological contract are associated with undesirable organizational outcomes, such as increased turnover intentions and absenteeism, counterproductive behaviors, decreased willingness to go “above and beyond” one’s role to benefit an organization, decreased job satisfaction, and decreased in-role performance.[34,35]

Recommendations

Recommendations based on the evaluation were based on the hierarchy of controls. Low-frequency sound is difficult to attenuate with barriers or enclosures due to diffraction and surface propagation. It is minimally attenuated by common building structures. Thus, we primarily recommended control measures related to the methane flares such as using flare burners designed to generate lower noise and maintaining an optimal methane-to-air ratio during burning to decrease combustion turbulence that leads to sound generation. As administrative controls, we recommended that the workplace establish a formal system for reporting potentially work-related symptoms to better document symptoms and encourage employees with health concerns to seek evaluation from health providers with occupational medicine expertise and familiarity with noise-related exposures and their health effects. We also recommended improvements in communication about the situation and employee concerns and consideration of employees' perceptions of risk and willingness to return to the vacated campus.

Limitations

One limitation of our evaluation was that it was not possible to characterize sound levels or noise frequency distributions that occurred during the loud noise and vibration incidents. Our measurements were done during normal flare operations and in unoccupied campus buildings after relocations. No similar loud noise and vibration incidents occurred during our evaluation. However, we were able to measure differences in one-third octave band noise levels and estimate the effects of a methane flare being on and off without background noise. Second, based on the scope of the HHE request, we did not assess employees' noise exposures away from the campus or non-noise exposures at the campus. Third, information from interviews was based on self-report approximately 1 to 4 months after the incidents, which may have resulted in recall bias. In addition, concerns about whether the incidents posed a health risk or interactions among employees (e.g., sharing of experiences and symptoms) might have influenced employees' perceptions of whether symptoms were related to unusual sounds or vibrations. Fourth, not all relevant medical records for employees who reported symptoms were available for review, and not all symptoms might have been captured in medical records available for review. Finally, statistical tests might not have been able to detect differences due to the relatively small number of employees. Therefore, no definitive conclusions about the cause of the symptoms can be drawn.

CONCLUSIONS

Our evaluation illustrates that multiple factors need to be taken into account when addressing health concerns related to low-frequency noise and infrasound. After two loud noise and vibration incidents at a workplace located near a low-frequency noise source, approximately 80% of employees reported noticing unusual sounds or vibrations, some preceding the loud noise and vibration incidents. Sound levels measured in the absence of loud noise and vibration incidents were well below occupational exposure limits and levels associated with symptoms. However, higher noise levels in lower relative to higher frequencies resulted in a spectrum imbalance that exceeded noise levels recommended in some European guidelines, which may have increased the likelihood of noise-related annoyance concerns. Many employees reported symptoms that they thought were related to unusual sounds and vibrations at the workplace, but different explanations for symptoms among different employees were likely. Employees were concerned about communication surrounding the incidents and over half of employees reported that they were uncomfortable returning to work at the vacated campus. More studies evaluating the relationship between noise-associated annoyance, symptoms, and perceived risk of exposure to low-frequency noise and infrasound are needed.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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ETHICS APPROVAL AND INFORMED CONSENT

Health Hazard Evaluations are not considered human subjects research by virtue of NIOSH acting as a public health authority performing a public health investigation as directed by statute. Participants were informed of the purpose of the evaluation, their rights regarding confidentiality, and the voluntary nature of participation. Informed consent was provided verbally.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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Appendix Representative low-frequency noise levels (dB) across one-third octave band frequencies 6.3 to 100 Hz while flares were operating

Measurement location	6.3 Hz	8.0 Hz	10.0 Hz	12.5 Hz	16.0 Hz	20.0 Hz	25.0 Hz	31.5 Hz	40.0 Hz	50.0 Hz	63.0 Hz	80.0 Hz	100 Hz	Overall level
Admin bldg. Room 100	51.5	52.0	52.2	55.4	60.4	62.9	60.5	45.6	36.5	39.5	35.4	35.0	34.4	67.0
Admin bldg. Room 101	52.6	53.0	57.5	56.8	59.2	71.4	66.9	47.3	39.1	41.4	40.3	35.5	35.5	73.2
Admin bldg. Room 102	50.8	50.1	58.9	62.6	56.4	63.0	60.8	47.0	35.0	41.3	33.1	34.5	37.3	68.1
Admin bldg. Room 103	49.6	51.1	57.0	56.2	62.6	65.5	62.9	48.8	41.9	43.6	45.2	39.7	38.0	69.3
Admin bldg. Room 105	55.8	56.0	54.4	55.1	56.9	70.0	57.9	50.2	46.6	44.1	44.9	41.5	37.8	71.0
Admin bldg. Room 108	55.0	57.9	58.5	55.0	53.8	68.9	59.4	46.5	40.9	40.6	39.5	31.9	30.2	70.4
Admin bldg. Room 109	59.7	59.3	59.9	57.6	54.2	63.7	57.9	46.0	40.9	41.2	42.6	36.0	37.6	68.2
Admin bldg. Room 110	54.3	57.0	51.5	60.1	53.4	63.0	59.1	42.5	33.7	35.2	36.5	33.1	37.2	67.0
Admin bldg. Room 113	54.9	55.8	54.2	51.6	49.6	60.5	51.5	43.7	37.4	37.4	32.3	29.0	29.3	63.9
Admin bldg. Room 117	57.1	56.7	53.1	53.4	57.3	60.9	53.9	45.0	38.6	33.8	37.5	37.9	31.0	65.4
Admin bldg. Room 118	49.9	51.4	51.3	52.5	48.9	62.1	60.1	44.5	35.7	38.2	33.3	33.1	31.5	65.2
Admin bldg. Room 121	50.7	54.6	54.3	50.3	56.2	64.7	58.8	50.3	41.5	42.2	38.7	35.5	36.9	67.0
Admin bldg. Room 123	55.9	55.3	58.1	56.1	59.5	63.3	53.8	46.6	44.5	43.4	46.7	47.4	40.1	67.2
Shelter bldg. Main room	48.3	52.0	53.8	53.1	50.5	64.6	62.9	52.3	47.8	48.7	46.9	46.1	42.3	67.8
Shelter bldg. Socializing room	56.7	56.8	53.7	54.3	54.2	60.4	51.4	48.4	50.3	49.5	46.3	45.6	45.1	65.2
Shelter bldg. Check-in desk	52.0	52.2	52.1	53.2	59.5	63.2	60.7	51.6	48.3	47.1	43.3	41.6	46.6	67.2
Shelter bldg. Office area	54.0	58.5	60.8	58.2	56.7	65.6	58.4	48.6	44.8	38.4	40.7	36.0	46.4	68.9
Shelter bldg. Intake office	47.8	49.7	52.9	54.5	55.2	62.9	58.6	48.3	43.7	37.0	41.1	38.9	38.4	65.7
Parking lot - Location A	60.2	62.9	68.9	72.0	76.2	84.9	79.7	68.1	66.8	62.2	63.1	62.9	55.5	86.9
Parking lot - Location B	61.3	61.5	61.3	63.2	67.6	76.9	77.1	61.2	59.8	58.3	57.7	54.9	52.7	80.6
Parking lot - Location C	62.0	60.4	64.3	69.8	73.8	80.3	75.0	67.6	60.6	61.4	61.2	57.7	53.6	82.7
Parking lot - Location D	60.5	62.4	62.1	64.8	68.7	78.1	72.4	63.1	62.4	57.9	58.4	57.4	56.8	80.1
Grill area	53.4	55.0	57.8	60.4	64.8	75.8	70.7	60.2	61.2	56.9	57.1	56.1	35.8	77.7
Smoking hut	56.0	57.7	63.8	67.4	68.3	81.3	74.1	65.9	63.2	59.1	58.0	55.9	52.0	82.6
Blower no. 2 (1.8 m from blower)	65.0	70.6	75.3	76.5	71.8	84.6	80.4	68.3	76.5	72.5	72.6	61.1	55.6	87.8
Flare no. 1 (3 m from flare)	69.1	72.3	76.5	81.1	79.7	91.2	83.5	71.3	74.4	70.8	67.6	67.1	65.9	92.8
Flare control panel	63.2	68.1	74.5	80.2	82.4	94.2	87.7	76.5	74.7	66.6	66.4	53.1	52.3	95.6
City street behind shelter	70.4	69.3	71.6	69.4	67.3	71.5	66.2	66.6	65.1	68.1	80.3	71.5	68.4	83.2
City street across from public storage business	64.2	62.4	60.4	60.1	60.6	66.0	61.9	61.5	63.0	65.2	69.9	67.3	67.0	76.0
ACGIH threshold limit values	145 (frequency dependent)													150 (overall)

Abbreviation: ACGIH, American Conference of Governmental Industrial Hygienists.