Evaluation of Noise Exposures and Hearing Loss at a Forging Company

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Contents

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The cover photo is a close-up image of sorbent tubes, which are used by the HHE Program to measure airborne exposures. This photo is an artistic representation that may not be related to this Health Hazard Evaluation. Photo by NIOSH.

Highlights of this Evaluation

The Health Hazard Evaluation Program responded to a request from company management and representatives of the International Brotherhood of Boilermakers at a metal forging company to evaluate noise exposures and hearing loss.

What We Did

- We measured employees' noise exposures in the forging operations.
- We measured impact noise and noise levels across noise frequencies at forge hammers.
- We interviewed employees about noise exposures and hearing loss.
- We analyzed employees' hearing tests.

What We Found

- Noise levels near the forge hammers were very high (sometimes above 100 decibels). Most of the noise was caused by metal-to-metal contact, compressed air, and background noise from furnaces.
- Peak sound pressure levels during hammer strikes were above the NIOSH recommended ceiling limit of 140 decibels peak sound pressure level.
- Nearly all forge shop employees' noise exposures were above the NIOSH noise exposure limit of 85 decibels, A-weighted.
- Many employees had hearing loss and hearing worsened with years on the job and age.
- Some employees reported having permanent ringing in their ears because of noise exposure.
- Some employees did not insert foam ear plugs properly.

We measured noise exposures and impact noise in a forging operation. Impact noise levels at the hammers reached up to 155 decibels. Employees' noise exposures were above noise exposure limits. Noise exposures near the hammers were above 100 decibels, A-weighted. We recommended noise controls, using dual hearing protection when noise exposures were above 100 decibels, A-weighted, conducting hearing protector fit testing, and buying less noisy equipment when replacing or installing new equipment.

What the Employer Can Do

- Reduce noise caused by metal-to-metal contact.
- Maintain equipment to help reduce noise levels.
- Consult with equipment makers when purchasing new equipment or replacing equipment to buy equipment that makes the least amount of noise.
- Require employees who work near the forge hammers to use both ear plugs and earmuffs.
- Make sure employees wear their hearing protection properly.

- Test employees' hearing protection to make sure it fits well and protects them from noise.
- Enforce proper hearing protection use.
- Use NIOSH recommendations for evaluating employees' hearing tests.

What Employees Can Do

- Wear ear plugs and earmuffs when working near the forge hammers.
- Wear hearing protection properly.
- Tell your doctor that you work in areas with high noise levels and report any hearing problems to your doctor.

Abbreviations

ACGIH®	American Conference of Governmental Industrial Hygienists
AL	Action level
CFR	Code of Federal Regulations
dB	Decibels
dBA	Decibels, A-weighted
HTL	Hearing threshold level
Hz	Hertz
ISO	International Standards Organization
kHz	Kilohertz
NIHL	Noise-induced hearing loss
NIOSH	National Institute for Occupational Safety and Health
NRR	Noise reduction rating
OEL	Occupational exposure limit
OSHA	Occupational Safety and Health Administration
Pa	Pascals
PEL	Permissible exposure limit
REL	Recommended exposure limit
SPL	Sound pressure level
STS	Standard threshold shift
TLV®	Threshold limit value
TWA	Time-weighted average

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Introduction

The Health Hazard Evaluation Program received a request from company management and the International Brotherhood of Boilermakers. The requestors were concerned about forge shop employees' exposures to noise and their risk of hearing loss. The company produced heated metal-forged parts and components for aerospace and general industries. Forgings, which weighed up to several thousand pounds, were composed of metal alloys such as carbon steel, titanium, and nickel. The worksite included several production buildings. Forging operations were housed in two separate locations at the worksite. Forging equipment included pneumatic single-action die hammers, counter-blow hammers, mechanical forging presses, hydraulic presses, trim presses, and furnaces. The forge shop operated five days per week with three 8-hour shifts. About 100 employees worked in the forge shop, with about two-thirds of these employees on the first (day) shift.

Process Description

Metal ingots, some weighing up to 500 pounds, were first loaded into furnaces using large forklifts referred to as manipulators. The manipulators had a long straight 10-foot extension arm affixed to the front. A hydraulically operated mechanism at the terminal end of the extension arm could grasp and rotate ingots as needed (Figure 1). Ingots were heated in furnaces for an appropriate duration, depending on the ingot size and alloy properties, to achieve the necessary temperature (typically around 2,400 degrees Fahrenheit).

Figure 1. A manipulator transporting a molten forging. Photo by NIOSH.

Once ingots were heated to the appropriate temperature, manipulator operators moved the molten metal ingots from the furnaces and positioned them between the dies in the forge hammer or press. The hammer operator used a foot-operated control pedal to activate the hammer and shape the hot metal ingot into a forging with a series of vertical impact blows (Figure 2). Hammer helpers, referred to as oilers and scale blowers, assisted by spraying the die with chemical releasing agent to prevent the ingot from sticking to the die. Compressed air was used to blow excess scale off the forging during the hammer process. Once the hammering process was complete, manipulators moved the forging to trim presses where excess metal was removed. Completed forgings were then moved by manipulators to the heat treat area outside of the forge shop where furnaces and quench media (oil, water, still air, fan air, cooled air) were used to give the forging the necessary metallurgical properties.

Metal dies were custom machined on site in a work area outside the forge shop. The dies were changed by die operators or machinists as needed, typically two or three times per shift. Maintenance mechanics and hammer repair personnel worked throughout the forge shop during the workday.

Figure 2. Hammer operator (right) and hammer helper (left) at forge hammer. Photo by NIOSH.

Methods

Our objectives included evaluating the following:

- Forge shop employees' full-shift time-weighted average (TWA) noise exposures
- Impact noise near hammer forges
- One-third octave band noise frequency levels
- Potential noise control options
- Hearing loss trends among forge employees
- Hearing loss symptoms among current employees

During our site visit, we measured the full-shift personal noise exposures of 38 production employees in 11 job titles. Because previous research had shown that noise dosimeters did not adequately measure impulsive noise levels greater than 140 decibels (dB) [Kardous and Willson 2004; Kardous et al. 2003], we measured impact noise at four forge hammers and one press using a noise measurement system designed by National Institute for Occupational Safety and Health (NIOSH) researchers based on a system used for previous NIOSH research [Kardous et al. 2005; Yan et al. 2004]. We took 7–25 measurements at each location and each measurement lasted 5–50 seconds in duration. The total measurement time at each location ranged from about 4–7 minutes. We also measured one-third octave band noise levels at these locations. For each impact noise and one-third octave band measurement, we simultaneously took measurements at two separate locations: within a few feet of the forge hammer and at a distance of about 6 feet.

We invited all 76 employees working first shift in the forge shop during the site visit to participate in confidential medical interviews. Twenty-eight employees agreed to participate. The interviews included work history, current and past hearing protector use, hearing protector training, and reports of hearing loss. We also reviewed the company's hearing conservation program and Occupational Safety and Health Administration (OSHA) Form 300 Log of Work–Related Injuries and Illnesses for OSHA recordable standard threshold shifts (STS).

After the site visit, the company provided us with an electronic database of 1,531 historical audiograms for 104 current or former forge shop employees. For employee privacy, we removed personal identification information from the audiometric test records. We used NIOSH audiometric quality assurance screening guidelines, detailed in Appendix C, to identify and remove audiograms that were incomplete or had audiometric patterns indicating hearing loss that could have resulted from non-occupational factors or inaccurate audiometric thresholds [Franks 1999]. Following screening, we analyzed employee audiometric test history to assess hearing loss. We compared the results to an International Standards Organization (ISO) unscreened reference population [ISO 1999]. For analysis, we used SAS Institute SAS® version 9.3 software.

Details on the methods used for noise dosimetry, impact noise measurements, and hearing loss analysis are provided in Appendix C.

Results and Discussion

Personal Noise Exposures

Table 1 provides a summary of personal noise exposure measurements by job title. OSHA and NIOSH measure and calculate noise exposures in slightly different ways. For an 8-hour work shift, the NIOSH recommended exposure limit (REL) is 85 decibels, A-weighted (dBA), the OSHA action level (AL) is 85 dBA, and the OSHA permissible exposure limit (PEL) is 90 dBA. Additional details on differences between NIOSH and OSHA noise exposure limits are provided in Appendix B. One or more employees in the jobs we monitored had full-shift noise exposures at or above the NIOSH REL and OSHA AL. In addition, one or more employees in all the job titles we monitored, except manipulator helper, trimmer, heating specialist, and maintenance mechanic and hammer repair, had full-shift noise exposures above the OSHA PEL.

Table 1. Range of full-shift TWA personal noise dosimetry measurements (dBA)

Job title	Number of measurements	Results based on OSHA AL criterion	Results based on OSHA PEL criterion	Results based on NIOSH REL criterion
Hammer operator	10	85–102	80–102	88–107
Hammer help (Scale blower and Oiler)	5	83–105	80–105	88–111
Manipulator operators	7	93–98	92–97	96–101
Manipulator helper	1	89	87	90
Trimmer	1	88	87	93
Inspector	2	91–92	91	96
Heating specialist	2	79–85	72–83	84–93
Maintenance mechanic and hammer repair*	4	84–86	78–83	88–91
Fork truck driver	4	89–92	86–91	91–95
Supervisor	2	82–90	80–90	88–95
Noise exposure limits (8-hour TWA)		85	90	85

* Maintenance mechanic and hammer repair jobs were grouped together for this summary table.

The primary source of noise exposure for jobs at or near the hammers (hammer operators, hammer helpers, manipulator operators) was impact noise from the hammers striking forgings and dies. Each forging typically required 5 to 15 hammer strikes of varying intensity. In addition, noise from compressed air that employees used to blow scale off forgings and spray chemical releasing agent onto the die contributed to noise exposures. This likely led to slightly higher noise exposures for the hammer helpers compared to the hammer operators. Noise from the furnaces contributed to background noise in the work area.

Based on NIOSH noise measurement criteria, 7 of 10 hammer operators, 4 of 5 hammer helpers, and 2 of 8 manipulator operators had full-shift TWA noise exposures greater than 100 dBA. Using OSHA measurement criteria, 2 of 10 hammer operators, 2 of 5 hammer helpers, and none of the manipulator operators had TWA noise exposures above 100 dBA. NIOSH and OSHA recommend the use of dual hearing protection (i.e., the combination of insert hearing protectors and earmuffs) when TWA noise exposures are above 100 dBA. Our noise exposure measurement results for hammer operators were similar to those reported by Taylor et al. [1984] in a study of hammer forge workers in seven different facilities in the United Kingdom. Hammer operators' TWA noise exposures in those facilities reached 108 dBA. In addition, Suvorov et al. [2001] found hammer operators' TWA noise exposure at an auto company forge workshop were 104–105 dBA.

Daily TWA exposures are highly influenced by the length of time exposures that exceed 100 dBA. For a noise exposure of 100 dBA, the NIOSH REL is exceeded after 15 minutes, the OSHA AL is exceeded after 1 hour, and the OSHA PEL is exceeded after 2 hours. The differences between the NIOSH REL and OSHA AL, which both have an exposure limit of 85 dBA, is due to NIOSH using a 3-dB exchange rate and OSHA using a 5-dB exchange rate for noise dose accumulations (Appendix B).

Figure 3 provides the noise exposure time history profile for a hammer operator and manipulator operator working at Hammer 80. These jobs had similar noise exposure time history profiles, but noise exposure decreased as distance from the hammer increased. The noise exposure level for the hammer operator reached up to 125 dBA during production runs. The manipulator operator worked further from the hammers while traveling to and from the furnace, hammer, and trim press. As a result, the manipulator operator's noise exposure during production runs was lower but reached 115 dBA at times. These employees' noise exposures decreased to approximately 65–70 dBA when they left the production area and went to a break room during work breaks and during die changes, which typically occur two to three times per shift. Noise exposure time history profiles for employees working at other hammers had similar patterns.

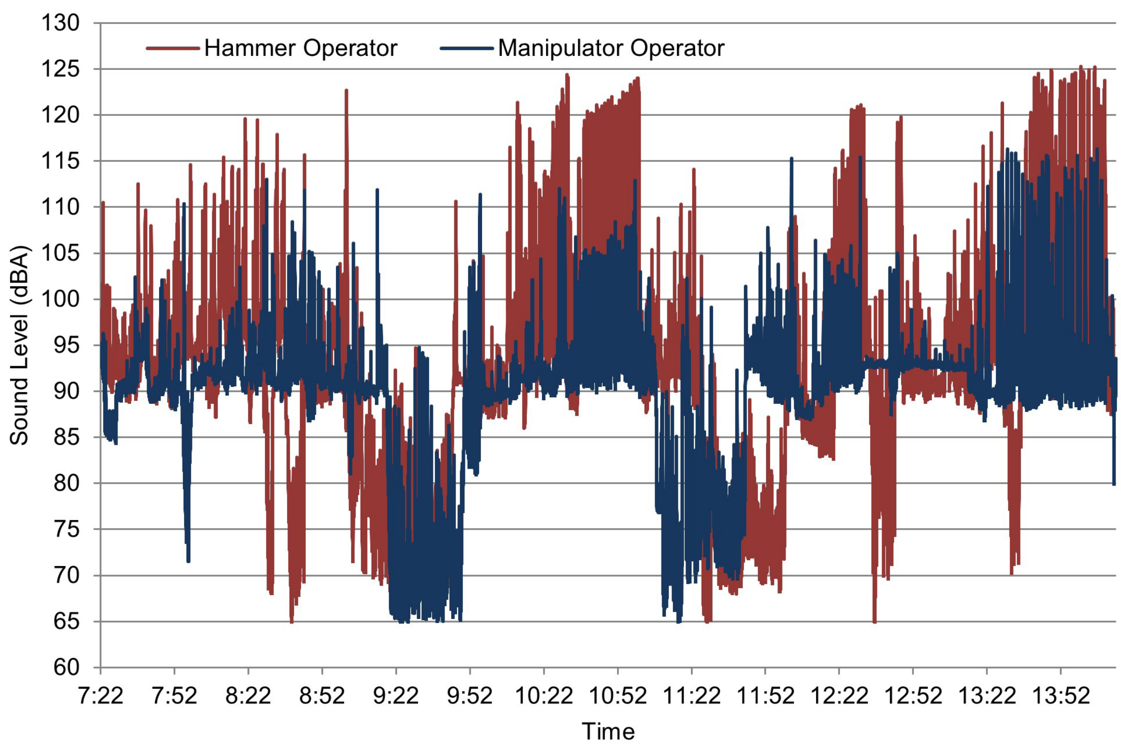

Figure 3. Noise exposure time history profile for a hammer operator and manipulator operator working at Hammer 80.

Noise exposure time histories and sound level measurements showed that noise exposures near the hammers were over 100 dBA during forging. Using the noise measurement data downloaded from the dosimeters, we calculated the overall amount and percent of time noise exposures exceeded 100 dBA for each job title that was monitored. We also calculated the amount of time and percent time exposures exceeded 90 dBA. These results are provided in Table 2. Jobs near the hammer (hammer operator, hammer helper, and manipulator operator) had the highest percentage of time in which noise exposures exceeded 100 dBA. In addition, noise exposure for employees in these jobs were above 90 dBA for slightly more than 50% of the work shift, on average.

The number and length of production runs at the hammers varied each shift depending on the type of part forged, size of forged parts, production rate per part, number of parts in the job order, and hammer downtime due to changing dies or maintenance needs. Employees' daily TWA exposures also varied on the basis of the number of production runs, number of hammer strikes per part, and force of each hammer strike.

Table 2. Percent time that noise exposures exceeded 100 dBA and 90 dBA

Number of measurements	Job title	Noise exposures > 100 dBA (Percent time)	Noise exposures > 90 dBA (Percent time)
10*	Hammer operator	< 1–18	12–79
5*	Hammer helper (scale blower and oiler)	1–26	12–76
7*	Manipulator operators	6–17	34–65
1	Manipulator helper	< 1	42
1	Trimmer	3	23
2	Inspector	5–8	32–37
2	Heating specialist	< 1–3	4–6
4	Maintenance mechanic and hammer repair	1–2	9–16
4	Fork truck driver	1–8	33–47
2	Supervisor	1–5	11–29

*Data for one of the measurements for these jobs was not available because of dosimeter download fault

Impact Noise Exposures

Forge hammer strikes generate substantial impact noise. Figure 4 shows the sound pressure waveform for a single strike at a counter-blow hammer. The hammer strike is characterized by a large peak in sound energy during the initial 0.1 seconds caused by sudden deceleration of the upper die and ram upon impact, which is then followed by "ringing" of decreasing intensity over time over the subsequent 0.5 seconds. The ringing is caused by vibration of the hammer forge structure, can last for several tenths of a second, and accounts for most of the sound energy generated by a hammer strike [Lam and Hodgson 1993]. Reduction of the ringing could reduce the TWA noise levels from each hammer strike. The sound pressure time-waveform of the impact is recorded in units of pascals (Pa). The relationship between Pa and dB is shown by the following formula:

$$dB = 20\ \log_{10} \frac{p(t)}{2 \times 10^{-5}}$$

The peak sound pressure of 190 Pa for the hammer strike shown in Figure 4 results in a peak SPL of 140 dB for this impact.

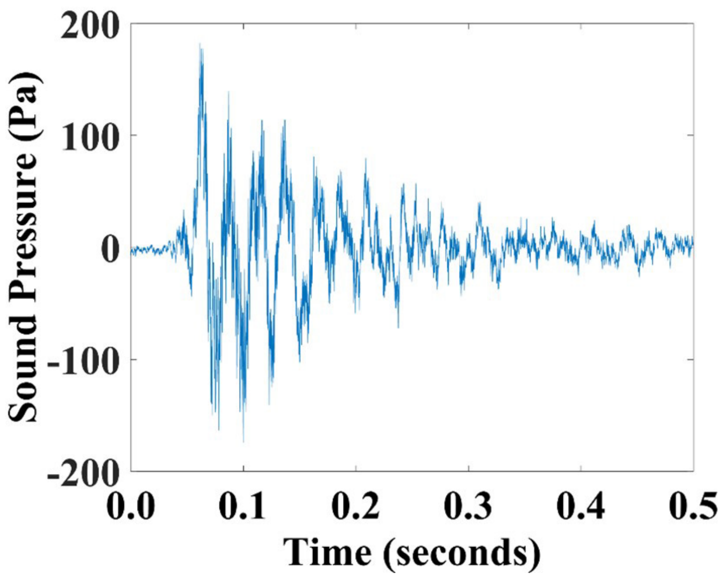

Figure 4. Typical sound pressure waveform for single hammer strike at a counterblow hammer.

The number, impact noise intensity, and sequence pattern of hammer strikes per forge part varied by size and type of part. Smaller or less complex parts usually required fewer hammer strikes than larger or more complex parts. Figure 5 shows impact noise for a sequence of 15 hammer strikes for a single metal part at the counterblow hammer. These hammer strikes occurred over a period of about 20 seconds with about one second of elapsed time between each strike. As can be seen in the figure, not all hammer strikes generate the same sound pressures. The highest sound peak tends to occur during die-to-die impact after the part has been completely forged into its final shape [Rivin 2007].

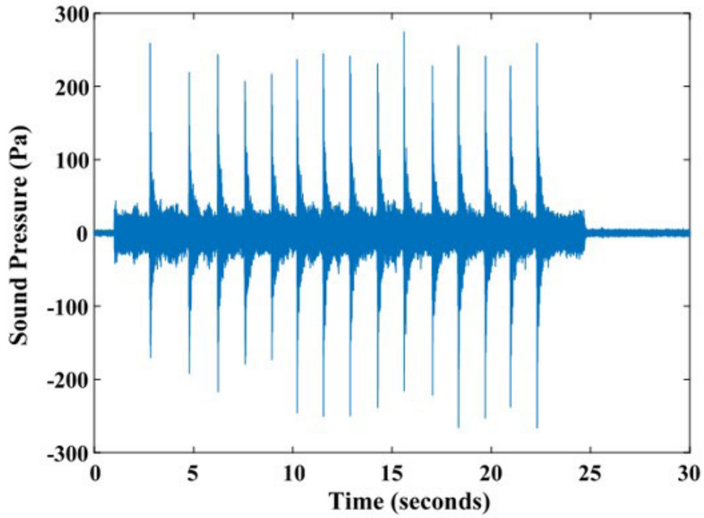

Figure 5. Sequence of hammer strikes for a single metal part at a counterblow hammer.

Peak SPL characteristics of impact noise at Press AZ164 and four hammers are summarized in Table 3. The highest peak SPL at the press was 128 dB. The maximum peak SPL during hammer impacts were 143–155 dB and averaged 136–143 dB. The peak SPLs at the hammers were generally similar to those reported in other studies of noise in hammer forges [Kamal et al. 1989; NIOSH 2016; Sulkowski et al. 1999; Suvorov et al. 2001; Taylor et al. 1984].

Table 3. Impact noise characteristics

Location of measurement	Peak range (dB SPL)	25% to 75% percentile	Average peak (dB)	Time between impacts robust mean (seconds)
Press AZ164	115–128	117–123	121	1.7
Hammer 25 (single-action)	116–155	120–136	136	1.2
Hammer 73 (single-action)	116–149	129–144	140	1.2
Hammer 85 (counterblow)	116–143	137–141	139	1.4
Hammer 80 (counterblow)	137–148	141–144	143	1.6

Peak SPLs during hammer strikes ranged from 116 dB to 155 dB. Figure 6 shows the proportion of peak SPLs in three sound level ranges at four different hammers and a press. No peak exceeded 130 dB (SPL) at the press, but 48%–100% of the peaks at the hammers were greater than 130 dB (SPL). The counterblow hammers (Hammer 85 and Hammer 80) had a greater percentage of peaks above 140 dB (SPL) (62%–95%) compared to single-action die hammers (hammer 25 and hammer 73) which had 24%–41% of the peaks above 140 dB

(SPL). This may be because the counterblow hammers were larger and generated greater overall force during the hammer cycle. The total number of impact noise peaks greater than 140 dB (SPL) that hammer operators are exposed to on a given day will depend on the type of forging, number of production runs, number of parts per production run, and number of hammer strikes per part. This number could range from a few hundred to a few thousand per day.

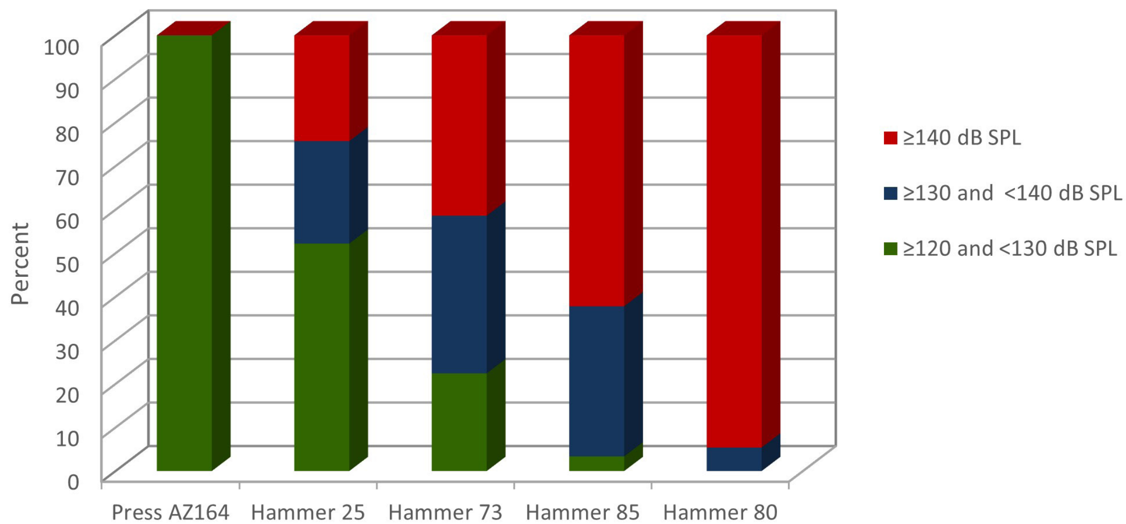

Figure 6. Proportion of impact peak SPLs levels within three different ranges during hammer strikes

One-third Octave Band Noise Frequency Analysis and Noise Control

Most workplace noise is broadband noise distributed over a wide range of frequencies. For analysis of the frequency distribution characteristics of workplace noise, the frequency spectrum is broken into smaller frequency bands. The most common being the octave band, which is defined as a frequency band where the upper band frequency is twice the lower band frequency. The one-third octave band further divides each octave band into three smaller frequency bands to provide more detailed information about noise frequency characteristics. Analysis of the frequency distribution characteristics of workplace noise can help identify predominate frequencies of noise sources and provide guidance on potential engineering or other noise control measures. One-third octave band measurement results are shown in Appendix A.

Noise from hammer forging results from several factors such as sudden deceleration of impacting dies, rapid sideways expansion of the forging during the strike, discharge of air from between dies, transmission of vibration to the surrounding floor, structural ringing of the hammer, and discharge of compressed air during spraying of the chemical releasing product.

The peak sound level generated by the hammer strikes is influenced by the magnitude and duration of the hammer blow pulse from decelerating dies, intensity of the strike, velocity of the strike, die design, cross sectional area of the forging and die, and transverse stiffness of the forging [Rivin 2007].

The highest one-third octave band sound levels at the two counter-blow hammers (Hammer 80 and Hammer 85) where we took measurements were at the frequencies 31.5–100 Hz and secondarily at 630–1,250 Hz. One-third octave band sound levels at two single-action die hammers where we took measurements were highest from 31.5–500 Hz at Hammer 25 and from 80–4,000 Hz at Hammer 73.

The low frequency noise below 125 Hz was most likely related to transmission of vibration from hammer strikes to the surrounding metal structure of the hammer and to the surrounding floor area. Noise in the 250–2,000 Hz frequencies at hammers most likely reflects sudden deceleration of the ram and upper die at impact and ringing of the machine structure immediately following impact. A research study evaluating and predicting ringing noise from forge hammers reported that the major energy content from deceleration of the ram occurred in noise frequencies of 500–1,000 Hz. The study also reported that noise from ringing occurs in the 2,000 Hz octave band [Lam and Hodgson 1993].

Hammer 80 and Hammer 73 also had some relatively high octave band sound levels above 8,000 Hz. This was likely due to noise from turbulent discharge of compressed air exiting spray nozzles (Figure 7) during scale blowing or spraying of chemical releasing agent onto the dies. Compressed air pressure could exceed 100 pounds per square inch. High pressure air exiting nozzles generates air turbulence and high noise levels, particularly high frequency noise. In addition, the end of the nozzle tips can have threading which also contributes to exiting air turbulence and noise. Open ended nozzles tend to use much more compressed air than may be necessary and can therefore be more costly. Some manufacturers of engineered compressed air nozzles have shown that open tube nozzles generate up to 10 dB more noise than properly engineered nozzles. In contrast, efficient air nozzles complete the required task, produce less noise, and reduce compressed air consumption by 30% to 60%, resulting in substantial cost savings [Saidur et al. 2010]. Nozzles specifically designed to complete the required tasks could be installed to use less compressed air and produce less noise.

Figure 7. Open tube nozzle with air pressure relief openings along the side. Photo by NIOSH.

High frequency noise exposures can also be reduced by using equipment enclosures or noise barriers [Driscoll 2022]. An enclosure for the hammers may not be feasible. However, installation and use of sound-insulated observation booths or sound barriers to stand behind could provide employees a place to observe operations when feasible, but with lower noise levels. Proper maintenance of equipment can also help reduce noise. For example, a worn or poorly maintained clutch in a hammer, worn out motor bearings, or loose metal parts that rattle in place generate unnecessary noise that can be eliminated.

Noise reduction should also be part of an overall long-term strategy. For example, when equipment is replaced, the amount of noise generated by the new equipment should be considered as part of the purchasing decision. “Buy Quiet” is a concept by which companies can reduce hazardous noise levels through their procurement process. Through this process, purchasers are encouraged to consult with equipment and tool manufacturers, compare noise emission levels for differing models of equipment and, whenever possible, choose equipment that produces less noise and vibration.

Hearing Conservation Program

The hearing conservation program was managed by the health and safety nurse practitioner and all forge shop employees were included in the program. Baseline and annual audiometric testing were completed through an external provider. Audiometric test frequencies included 0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, and 6 kHz. Audiometric testing sometimes included 8 kHz, but this had not been consistently done. NIOSH recommends that audiometry should include testing at 8 kHz to improve decisions about probable etiology of identified hearing loss [NIOSH 1998]. If an employee’s audiogram indicated a hearing threshold shift, the employee was retested within 30 days to confirm the shift. The nurse practitioner managed employees’ audiometry records which were kept in an audiometric history database. Employees with hearing-related problems identified during audiometric testing were informed of their abnormal hearing test results and were referred to their healthcare provider for further evaluation. However, the nurse practitioner reported that many employees did not go.

The company provided 15 different types of foam-insert earplugs or earmuffs to noise-exposed employees. According to the hearing protection device manufacturers, the noise reduction rating (NRR) for these hearing protectors ranged from 21 dB to 33 dB. The manufacturers' NRR is a rating of the hearing protector attenuation which is determined by the manufacturer using laboratory test procedures specified by the Environmental Protection Agency [EPA 1978]. However, subject fit testing research has shown that the actual noise attenuation of hearing protection during use varies. Attenuation can be much less than the manufacturers' reported NRR when the hearing protection fits poorly, but greater attenuation than the manufacturers' reported NRR may be possible with well-fitting hearing protectors [Berger et al. 1996, 1998; Franks et al. 2000; Joseph et al. 2007; Murphy et al. 2011]. Similarly, NIOSH testing of ear plug attenuation in a mannequin head test fixture during a previous health hazard evaluation also showed hearing protector attenuation ranging from below to above the manufacturers' reported NRR [NIOSH 2016].

Employees had the option to wear dual hearing protection, i.e., both insert ear plugs and earmuffs, but it was not required. Most employees wore foam insert ear plugs, but we observed that a few hammer operators used dual protection. During our evaluation, we observed that some employees who chose to use insert ear plugs did not appear to fully insert them into their ear canal. Research has shown that ear plugs can appear to be properly inserted into the ear canal but still provide minimal noise attenuation because of poor fit due to factors such as improper insertion technique and incorrectly sized ear plug for the wearer [NIOSH 1998, Smalt et al. 2021]. Hearing protectors must attenuate noise levels to less than 85 dBA to provide adequate protection. Noise attenuation of insert-type hearing protection depends on the type of hearing protector, shape of the user's ear canal, how well the hearing protector fits, and proper insertion of the hearing protector. Several hearing protection manufacturers have developed methods for hearing protector fit testing to determine the attenuation employees receive from their hearing protection.

The company used computer-based hearing conservation training. All employees were required to complete the training and receive an 80% score on the training module test. The health and safety nurse practitioner supplemented the training by showing employees the types hearing protectors that were available and instructing them on how to insert and wear earplugs.

Employee Interviews

During the site visit, we interviewed 28 (37%) of the 76 first shift forge shop employees who agreed to participate in confidential medical interviews. We interviewed these employees privately about hearing protector use, hearing loss, and other hearing-related concerns. All 28 employees we interviewed were male and had a median age of 53.5 years (range: 21 to 65 years). The median duration of employment in their current job at the facility was 29.5 years (range: 2 weeks to 46 years). Many reported that they had started working at the company shortly after graduating from high school, which explained the long durations of employment. Reported job titles of those interviewed included heating specialist (2), maintenance mechanic (1), forge shop helper (4), hammer operator (3), production press operator (1), trimmer setter (1), press operator (1) fork truck operator (2), manual operator (3), inspector (1), and ring roll operator (1).

All interviewed employees reported that they always wore hearing protection while working in the forge shop, and all reported using foam insert earplugs. One employee reported using dual protection, but only intermittently. During the open feedback portion of the interview, several employees noted that earmuffs were uncomfortable, particularly during hot weather, and therefore they chose not to wear earmuffs. Some employees reported that they did not wear earmuffs due to a vacuum sensation they felt under the earmuffs. They attributed this sensation to the pressure wave from the large hammers. All employees reported receiving training on hearing protection. Twenty-two (76%) employees reported being trained during new employee training on how to wear their hearing protection, while 5 (18%) employees reported their training on hearing protection occurred after they had started working at this facility. One employee was unsure when training was done relative to starting work.

We asked all 28 interviewed employees if they had any hearing loss. Seventeen (61%) reported having hearing loss. We asked the employees reporting hearing loss to rate their loss as mild (n = 6), moderate (n = 7), or severe (n = 3). Table 4 provides a summary of reported hearing loss.

Table 4. Hearing loss reported by interviewed employees (n = 28)

	Number of interview participants (percent)	Median years of age (range)	Median years employed at facility (range)
No hearing loss	11(39%)	49 (21–55)	18 (< 1–38)
Mild hearing loss	6 (35%)	48 (30–58)	19 (3–41)
Moderate hearing loss	7 (41%)	59 (50–64)	37 (19–46)
Severe hearing loss	3 (18%)	57 (57–62)	40 (34–42)
Hearing loss not specified	1 (4%)	65 (N/A)	30

The 17 employees who reported having hearing loss were also asked if they ever had a hearing test that documented hearing loss. Fourteen (82%) of these employees reported that they had a previous hearing test showing hearing loss. Three (18%) were unsure if any of their previous hearing tests showed hearing loss (two reported having mild loss and one reported having moderate hearing loss). Although all interviewed employees reported receiving training on and consistently using hearing protection, during the interviews 61% reported having hearing loss. These results may indicate that hearing protection was not sufficiently attenuating noise exposures. Either because the ear plugs alone did not provide enough protection or that employees were not adequately inserting the ear plugs into the ear canal to achieve maximal attenuation. During the site visit we observed instances where ear plugs were not deeply inserted into the ear canal. In addition, some employees reported that compliance with hearing protection use was not optimal in the past. The health and safety nurse practitioner also described that in the distant past employees sometimes used cotton balls instead of ear plugs for hearing protection.

Several of the interviewed employees who reporting having abnormal hearing test results also reported that they did not go for follow-up medical evaluation. They further reported that medical follow-up seemed unnecessary because co-workers who had medical follow-ups were told that the hearing loss was due to noise exposure at work, which they felt was obvious. Because forge shop employees have substantial workplace noise exposures, it is likely that most cases of hearing loss are noise induced. However, proper medical follow-up is important to identify whether other medical conditions are contributing to hearing loss. The nurse practitioner informed us that previously an employee was found to have an acoustic neuroma during their follow-up evaluation for an abnormal annual hearing test. Employee training should emphasize the importance of follow-up medical evaluations for determining whether employees have medical conditions causing hearing loss and starting medical treatment if needed.

Because of the relatively low number of employees interviewed, our findings may not be generalizable to all forge shop employees. In addition, we did not ask about noise exposures or use of hearing protection outside of work. Therefore, we were not able to determine whether non-occupational exposures may have also been a factor in the reported hearing loss.

Review of OSHA 300 Log of Reportable Injuries and Illnesses

We reviewed OSHA's Form 300 Log of Work-Related Injuries and Illnesses for 2003–2006. A majority of recordable injuries and illnesses were musculoskeletal injuries such as lacerations, contusions, sprains/strains, and extremity fractures. Back strains were often associated with lifting or maneuvering heavy items into place and many of the lower extremity sprains and strains (knee/ankle) were associated with getting onto or off of forklifts or related to slips, trips, and falls. Other recordable injuries included STSs, foreign bodies in the eyes, mostly among workers in the grinding or forging areas, and carpal tunnel syndrome in office staff. An ear-related injury from an ear canal infection associated with use of ear plugs was reported once during this period.

Table 5 summarizes recordable STSs. OSHA defines a recordable STS as an average change in hearing threshold, relative to the baseline, of 10 dB or more across the audiometric test frequencies of 2 kHz, 3 kHz, and 4 kHz; in conjunction with a hearing level of 25 dB above audiometric zero averaged across those frequencies. The total number of recordable STSs ranged from 7 to 15, representing 11%–23% of all recordable injuries and illnesses. Employees with recordable STSs worked in the following areas: forge shop, heat treat, maintenance, die engineering, shop cribs, product assurance, processing, steel stores, building 66, building 29, trucking, and human resources. As a percent of all STSs reported, employees in the forge shop accounted for 14%–21% of the STSs.

Table 5. Summary of recordable injuries and standard threshold shifts on OSHA 300 logs

Year	Number of employees	Number of recordable injuries	Number of STS reports (percent of all recordables) among all employees	Number of STS reports (percent of all STS) among forge shop employees
2003	742	66	15 (23)	3 (20)
2004	698	63	7 (11)	1 (14)
2005	730	73	12 (16)	2 (17)
2006	774	68	14 (21)	3 (21)

Analysis of Audiometric History

The audiometric dataset provided by the company initially included 1,531 historical audiograms from 104 current or former forge shop employees across the years 1970 to 2007. Before longitudinal analysis of hearing loss, we used NIOSH audiometric quality assurance screening guidelines [Franks 1999] to eliminate audiograms with inaccurate thresholds, incomplete audiograms, or audiograms that had patterns indicating that hearing loss could be a result of non-occupational factors. Audiometric screening based on these guidelines has been used in previous NIOSH research [Heyer et al. 2011; Masterson et al. 2013]. After screening, the dataset had 1,280 audiograms from 98 employees. The majority of audiograms eliminated were due to large intra-aural differences in the same frequency thresholds between ears, which are rarely caused by occupational noise exposures [Arslan and Orzan 1998]. The mean number of audiograms per employee was 12.3 (range: 1–27). The company was able to provide hire dates for some of the employees (n = 80) in the dataset. The average duration of employment for these employees was 24.5 years (range: 1.3–42.5 years).

We looked for trends in the percent of forge shop employees identified each year with hearing threshold shifts or NIOSH-defined material hearing impairment. OSHA and NIOSH use different hearing threshold shift criteria. OSHA defines an STS as an average change in hearing threshold, relative to the baseline, of 10 dB or more across the audiometric test frequencies of 2 kHz, 3 kHz, and 4 kHz. NIOSH defines a significant threshold shift as a change in hearing threshold, relative to the baseline, of 15 dB or more in any of the audiometric test frequencies. Research has shown that NIOSH criteria is more sensitive than OSHA criteria for identifying threshold shifts [Rabinowitz et al. 2007]. NIOSH defines material hearing impairment as an average hearing threshold level (HTL) for both ears of 25 dB or more at 1 kHz, 2 kHz, 3 kHz, and 4 kHz [NIOSH 1998]. From 1983 to 2007, we observed year-to-year variation but did not observe a sustained upward or downward trend in the percent of employees identified each year with hearing threshold shifts or NIOSH-defined material hearing impairment (Figure 8). The average annual percentage of employees with a NIOSH significant threshold shift was 23% (range = 9%–52%). The average annual percent of employees with an OSHA STS was lower at 12% (range = 0%–23%). The average annual percentage of those with material hearing impairment was 16% (range = 0%–29%), based on the NIOSH definition.

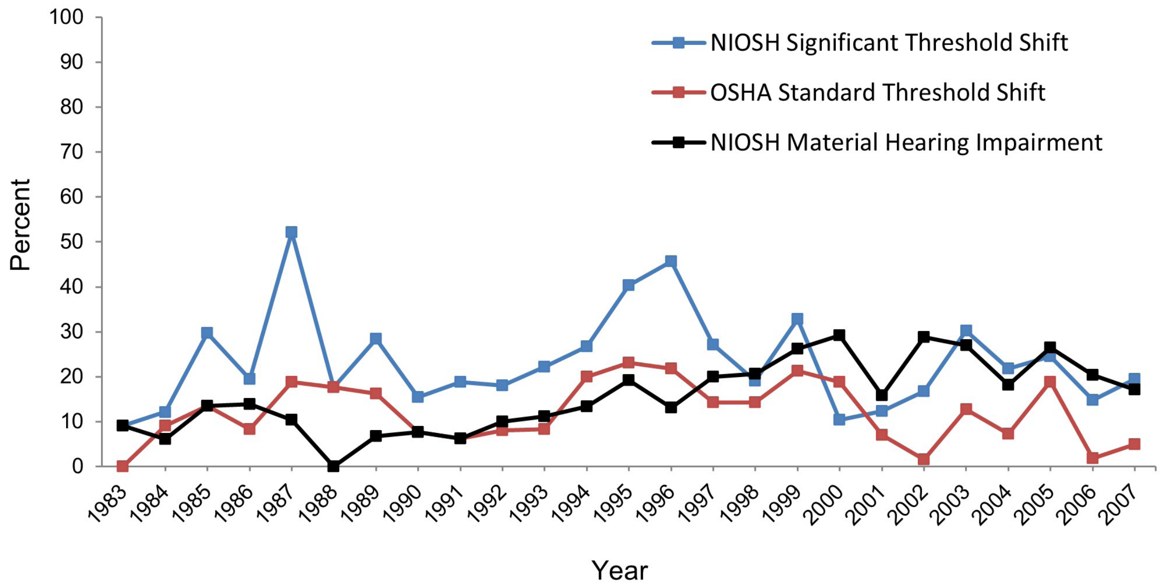

Figure 8. Percent of employees each year with a NIOSH significant threshold shift, OSHA STS, and NIOSH defined material hearing impairment.

Our analysis of the audiometric history for the 98 forge employees who had more than one valid audiometric test completed indicated that 82 (84%) had experienced a hearing threshold shift since their baseline audiogram, based on NIOSH significant threshold shift criteria. Using OSHA STS criteria, 72 (73%) had experienced an OSHA STS since their baseline audiogram. Similarly, an analysis of a large audiometric database of aluminum company workers by Rabinowitz et al. [2007] also found that more workers were identified with hearing threshold shifts using NIOSH significant threshold shift criteria than were identified using OSHA STS criteria.

We found that 12% (10/82) of the employees with a NIOSH significant threshold shift had not advanced to an OSHA STS. However, every worker with an OSHA STS previously had a NIOSH significant threshold shift. For the 72 employees who had an OSHA STS, we analyzed the length of time between when employees were first identified with a NIOSH significant threshold shift to when they were first identified with an OSHA STS. On average, 12.9 years (range: 0–36.7 years) elapsed between when employees were first identified with a NIOSH significant threshold shift to when they were first identified with an OSHA STS. The company used OSHA criteria for identifying STS in annual audiograms, as required by regulations. Our results suggest that using NIOSH criteria to identify significant threshold shifts could lead to earlier identification and intervention to prevent further hearing loss for many of the workers. This could reduce the number of employees who eventually progress to an OSHA STS or further hearing loss.

For workers (n = 80) in the age groups < 25, 25–34, 35–44 years of age who had a normal baseline audiogram (HTL < 20 dB) preceding hearing threshold shifts we evaluated the length of time from their baseline audiogram to a hearing threshold shift (Table 6). Overall, 9.1 years elapsed from a normal baseline to a NIOSH significant threshold shift. Using OSHA STS criteria, a longer period of 13.8 years elapsed before reaching an STS. When stratified by age group, based on NIOSH significant threshold shift criteria, we saw a decrease in years from normal baseline to NIOSH significant threshold shift by increasing age. Similar to what we observed using NIOSH criterion, workers in the 25–34-year age group progressed to an OSHA STS faster than those in the < 25-year age group. That trend did not continue with the 35–44-year age group. Compared to the youngest age group, it is unclear why workers in the older age groups progressed to threshold shifts more quickly. Possible explanations could include assignment of older, more experienced workers to jobs with higher noise exposures or less consistent use of hearing protection. We did not have hearing protection use or job title information to further examine these possibilities.

Table 6. Mean number of years from normal baseline audiogram to NIOSH and OSHA threshold shifts, stratified by age at time of baseline audiogram

Age group (years of age)	Number of subjects	Years to NIOSH threshold shift	Number of subjects	Years to OSHA threshold shift
< 25	50	10.6	47	14.9
25–34	22	7.1	18	11.5
35–44	8	5.3	6	12.0
Overall	80	9.1	71	13.8

Table 7 shows HTLs for the forge employees stratified by age at the time of their most recent audiogram. The youngest two age groups had similar hearing thresholds at audiometric test frequencies greater than 0.5 kilohertz (kHz), and neither had substantial hearing loss. The under 25-year age group showed relatively worse hearing at 0.5 kHz. However, this age group only had two subjects, and this result might have occurred because of the effects of background noise or undiagnosed ear pathology in one or more of the test results, rather than evidence of poorer hearing at this frequency. Each progressively older age group had higher HTLs (worse hearing) than the preceding age groups, most likely due to the corresponding increase in tenure and corresponding years of noise exposure. The highest HTLs were in the 4 kHz and 6 kHz frequencies. Table 8 shows HTLs for the forge employees stratified by length of tenure. Audiometric test frequencies greater than 0.5 kHz showed that HTLs were progressively higher (worse hearing) with increasing tenure. The highest HTLs were in the 4 kHz and 6 kHz frequencies. This is a typical pattern for noise-induced hearing loss (NIHL) [NIOSH 1998].

Table 7. Hearing threshold levels by age group, based on age at time of most recent audiogram

Age group	Number of subjects	Mean tenure (years)	Hearing threshold levels in dB by test frequency					
			0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz
< 25	2	1.5	11.3	3.8	5.0	2.5	7.5	10.0
25–34	10	3.5	8.8	5.3	5.0	2.5	10.3	8.8
35–44	13	17.4	12.7	12.3	10.0	13.5	21.7	21.3
45–54	47	25.7	14.5	12.6	14.7	19.9	27.9	28.1
55–64	26	34.5	22.1	19.8	23.5	29.9	40.1	36.2

Table 8. Hearing threshold levels stratified by years of exposure

Tenure (years)	Number of subjects	Mean age (years)	Hearing threshold levels in dB by test frequency					
			0.5 kHz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz
< 2	8	30	11.3	3.8	3.1	3.4	8.4	9.7
2–4			(only 1 subject in this age range)					
5–9	5	48	8.3	8.1	8.3	5.8	19.2	17.1
10–14			(no subjects in this age range)					
15–19	16	47	12.2	11.4	11.1	16.1	25.8	19.5
20–29	11	49	13.2	15.0	19.8	23.9	26.8	28.4
≥ 30	35	56	21.0	18.8	21.6	25.9	35.0	35.3

The trend of worse hearing with age and length of tenure was also observed by Taylor et al. [1984] in a study of employees from seven forges in the United Kingdom. The HTLs in press operators and hammer operators in that study were higher than the HTLs we found in these forge employees. We did not have job title and work history information; therefore, our analysis of audiometric records included all forge shop employees and was not limited to only hammer and press operators. Therefore, our results may not reflect higher HTLs that might be more likely in jobs with the highest TWA and impact noise exposures, specifically those jobs closest to the hammer. Compared to the population studied by Taylor et al. [1984], the forge employees in this population may have had better use of hearing protection because of the OSHA hearing conservation standard that went into effect in 1983. During our site visit, all employees we observed wore hearing protection. In addition, during interviews and informal discussions employees reported consistent use of hearing protection.

Figure 9 shows the differences in HTLs after 10 years of noise exposure in the forge for workers who started working before 1980 compared to workers who started after 1980. Relative to the other audiometric test frequencies, HTLs were worse at 6 kHz. HTLs for forge workers starting after 1980 were lower than for workers who started before 1980. This may be further evidence of improved hearing protection use beginning in the 1980s after the OSHA hearing conservation standard went into effect.

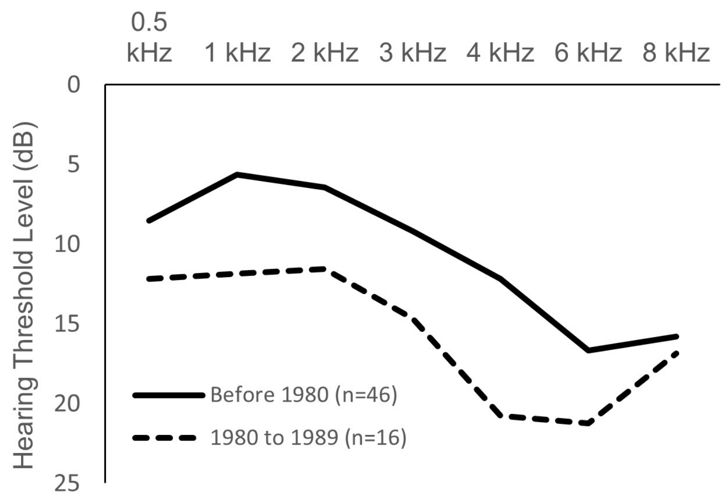

Figure 9. Comparison of HTLs after 10 years of noise exposure in forge workers by hire date (before or after 1980).

Figure 10 shows the HTLs in the forge population, stratified by age group, compared to an ISO reference population, which consists of unscreened workers from the ISO 1999:2013 standard, Annex B3, from the U.S. population [ISO 1999]. The 50th percentile HTLs for the forge population in this workplace was similar to the 50th percentile HTLs for the ISO reference population. For most of the age groups in this forge population the range of HTLs across the 10th to 90th percentile fell within the ISO reference 10th to 90th percentile range. Noise research has shown that exposure to impulsive noise or high level complex noise (combination of continuous and impulsive noise) is more likely to cause hearing loss than exposure to only continuous noise [Davies et al. 2012; Pfander et al. 1980; Qiu et al. 2020; Starck et al. 1988; Sulkowski 1980; Zhao et al. 2010]. Therefore, we might have expected the forge workers to have worse hearing than the reference population, which did not have impulsive noise exposure. Some potential hearing loss in this forge population may be mitigated by the heat wait periods built into the work cycle. Employees commonly spent the heat wait in quieter areas. The time spent in lower noise areas provides an opportunity for recovery of temporary hearing losses and may decrease the risk of permanent hearing loss [Kryter et al. 1966, Ryan et al. 2016].

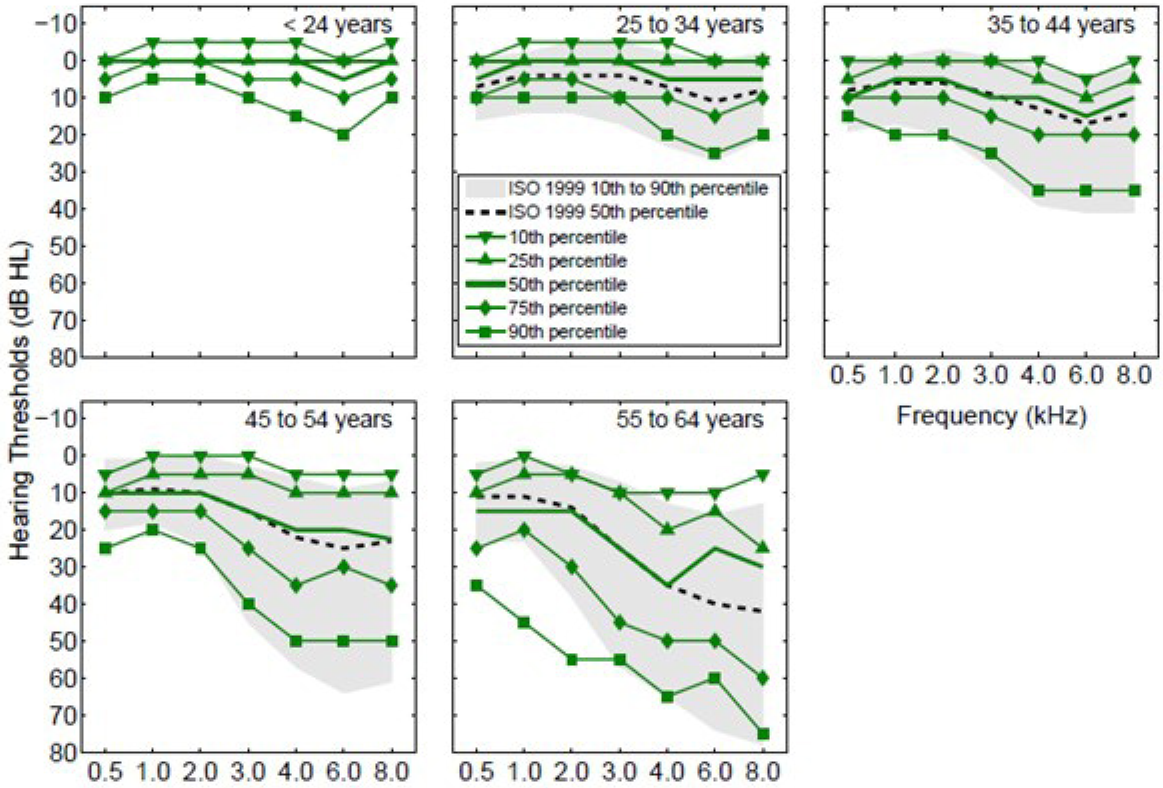

Figure 10. Comparison of forge worker HTLs to the ISO 1999:2013 standard, Annex B3 reference (unscreened) population HTLs.

Conclusions

All employees we monitored had full-shift noise exposures that exceeded the NIOSH REL and OSHA AL. In addition, full-shift noise exposures for employees in the following jobs were also above the OSHA PEL: hammer operator, hammer helper, manipulator operator, inspector, fork truck driver, and supervisor. Noise exposures for some of the hammer operators, hammer helpers, and manipulator operators were above 100 dBA. Peak noise levels during hammer impacts were above 140 dB and at one of the hammers reached a peak of 155 dB. Our analysis of the audiometric history for 98 forge employees, covering a 37-year period, showed that 84% had experienced a NIOSH-defined significant threshold shift, and 73% had experienced an OSHA STS since their baseline audiogram. The mean number of years from a normal baseline audiogram to a threshold shift was about 9 years for a NIOSH threshold shift and was about 14 years for an OSHA STS. Because of the high noise exposures and high impact noise levels, overall hearing levels among employees worsened with age and length of employment. This trend was also reflected by the results of employee interviews in which 61% of participating employees reported having some level of hearing loss.

Recommendations

Based on our findings, we recommend the actions listed below. We encourage the company to use a labor-management health and safety committee or working group to discuss our recommendations and develop an action plan. Those involved in the work can best set priorities and assess the feasibility of our recommendations for the specific situation at the facility.

Our recommendations are based on an approach known as the hierarchy of controls (Appendix B). This approach groups actions by their likely effectiveness in reducing or removing hazards. In most cases, the preferred approach is to eliminate hazardous materials or processes and install engineering controls to reduce exposure or shield employees. Until such controls are in place, or if they are not effective or feasible, administrative measures and personal protective equipment may be needed.

Engineering Controls

Engineering controls reduce employees' exposures by removing the hazard from the process or by placing a barrier between the hazard and the employee. Engineering controls protect employees effectively without placing primary responsibility of implementation on the employee.

1. Maintain all equipment to eliminate unnecessary rattles and compressed air leakages.
2. Replace open tube compressed air nozzles with nozzles that are specially designed to produce less turbulence and noise, and also meet OSHA safety standards for maximum air pressure.
3. Add closed cabs to the manipulators to reduce operators' exposures. If closed cabs are not feasible, a three-sided enclosure of the front and sides could help reduce noise exposures.

Administrative Controls

Administrative controls refer to employer-dictated work practices and policies to reduce or prevent hazardous exposures. Their effectiveness depends on employer commitment and employee acceptance. Regular monitoring and reinforcement are necessary to ensure that policies and procedures are followed consistently.

1. Implement a "Buy Quiet" program, which is a long-term strategy to reduce noise exposures when installing new equipment or replacing current equipment by purchasing equipment that generates less noise and less vibration. Information on Buy Quiet programs is available at http://www.cdc.gov/niosh/topics/buyquiet/.
2. Consult with acoustical noise control engineers who have expertise in forging industry noise reduction approaches for additional guidance on noise controls. The noise control engineers should be board certified by the Institute of Noise Control Engineers.
3. Continue to provide annual audiometric evaluations. To improve detection of potential hearing loss, use NIOSH criteria in addition to OSHA criteria to identify hearing threshold shifts. Include the 8 kHz frequency in audiometric tests. Refer to NIOSH

audiometric evaluation and monitoring recommendations at http://www.cdc.gov/niosh/docs/98-126/ for additional information on audiometric testing and hearing loss prevention programs.

4. Advise employees to report any hearing problems to their healthcare provider and to the company.

Personal Protective Equipment

Personal protective equipment is the least effective means for controlling noise exposures because of factors such as improper selection, poor fit, and improper or inconsistent use. Proper use of personal protective equipment requires a comprehensive program and a high level of employee involvement and commitment. The right personal protective equipment must be chosen for each hazard. Supporting programs such as training, change-out schedules, and medical assessment may be needed. Personal protective equipment should not be the sole method for controlling hazardous exposures. Rather, personal protective equipment should be used until effective engineering and administrative controls are in place.

1. Require hammer operators, hammer helpers, and manipulator operators to wear dual hearing protection, which includes ear plugs and earmuffs. For maximum protection, provide ear plugs that have a high level of noise attenuation.

2. Conduct hearing protector fit testing to determine the noise attenuation of the hearing protectors used by forge employees.

3. Ensure that workers are properly trained on how to wear hearing protection, specifically how to properly insert hearing protectors. Training should include demonstrations and an opportunity for workers to practice inserting hearing protectors properly. Enforce proper hearing protector use. Inform employees about the importance of also protecting hearing from noise exposures that might occur outside the workplace.

Appendix A: Figures

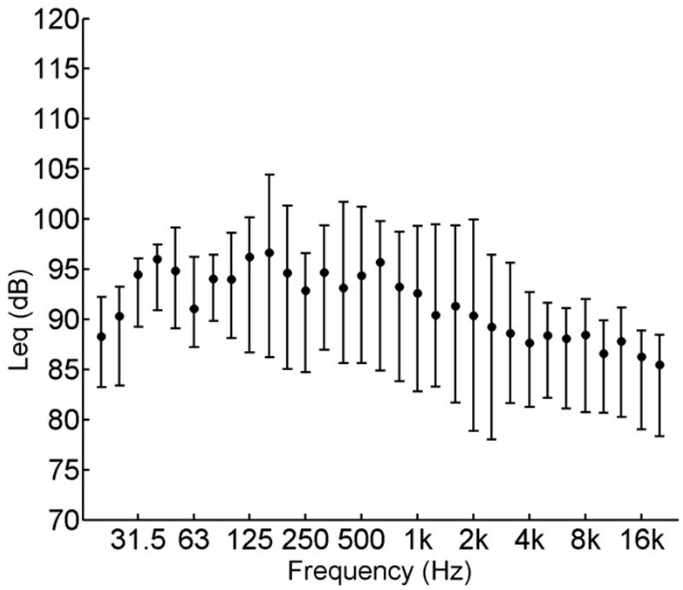

Figure A1. One-third octave band analysis for Hammer 25 (single-action die hammer).

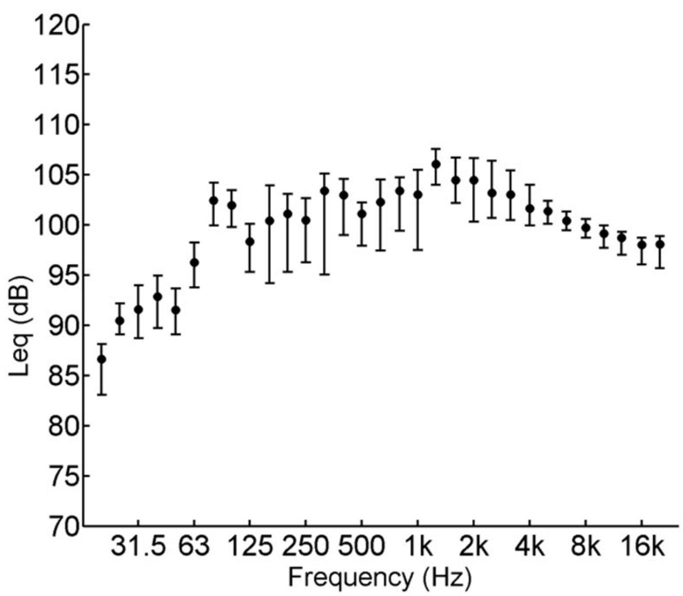

Figure A2. One-third octave band analysis for Hammer 73 (single-action die hammer).

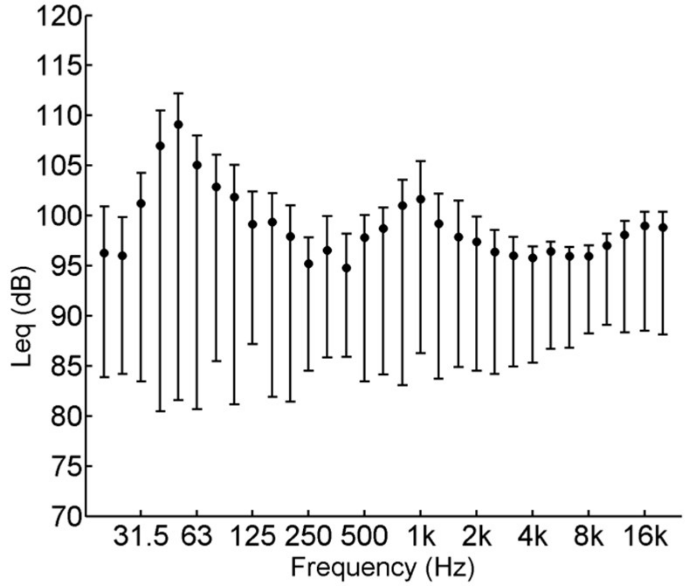

Figure A3. One-third octave band analysis for Hammer 80 (counterblow hammer).

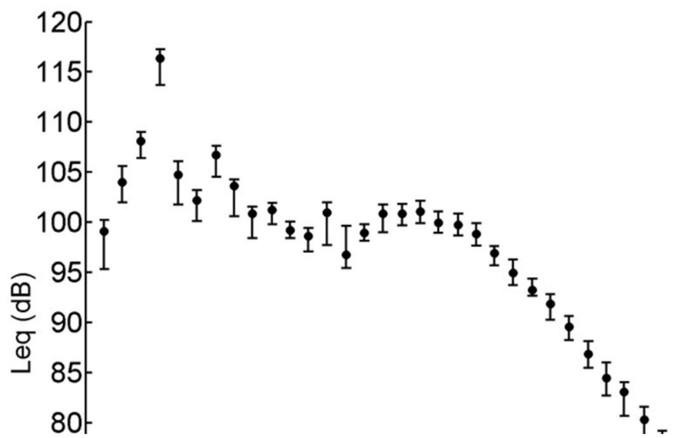

Figure A4. One-third octave band analysis for Hammer 85 (counterblow hammer).

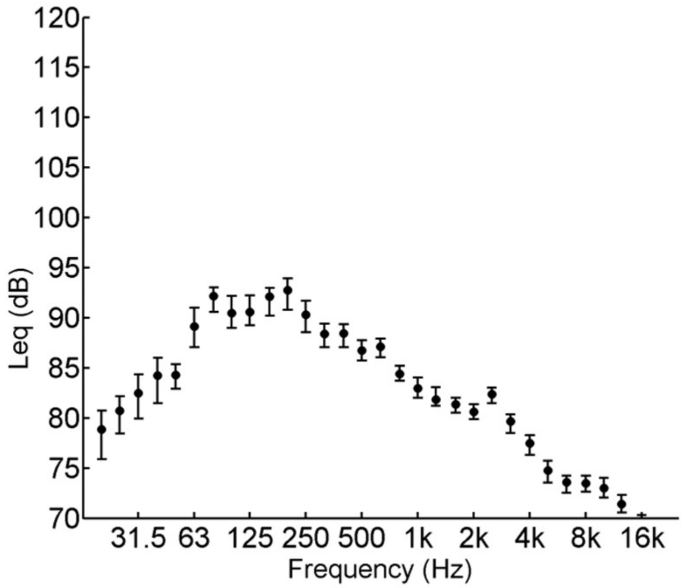

Figure A5. One-third octave band analysis for Press AZ164.

Appendix B: Occupational Exposure Limits and Health Effects

NIOSH investigators refer to mandatory (legally enforceable) and recommended occupational exposure limits (OELs) for chemical, physical, and biological agents when evaluating workplace hazards. OELs have been developed by federal agencies and safety and health organizations to prevent adverse health effects from workplace exposures. Generally, OELs suggest levels of exposure that most employees may be exposed to for up to 10 hours per day, 40 hours per week, for a working lifetime, without experiencing adverse health effects. However, not all employees will be protected if their exposures are maintained below these levels. Some may have adverse health effects because of individual susceptibility, a pre-existing medical condition, or a hypersensitivity (allergy). In addition, some hazardous substances act in combination with other exposures, with the general environment, or with medications or personal habits of the employee to produce adverse health effects.

Most OELs are expressed as a TWA exposure. A TWA refers to the average exposure during a workday. Some chemical substances and physical agents have recommended short-term exposure limits or ceiling values which should not be exceeded during a workday. In the United States, OELs have been established by federal agencies, professional organizations, state and local governments, and other entities. Some OELs are legally enforceable limits; others are recommendations.

The U.S. Department of Labor OSHA PELs (29 CFR 1910 [general industry]; 29 CFR 1926 [construction industry]; and 29 CFR 1917 [maritime industry]) are legal limits. These limits are enforceable in workplaces covered under the Occupational Safety and Health Act of 1970. NIOSH RELs are recommendations based on a critical review of the scientific and technical information and the adequacy of methods to identify and control the hazard. NIOSH RELs are published in the *NIOSH Pocket Guide to Chemical Hazards* [NIOSH 2007]. NIOSH also recommends risk management practices (e.g., engineering controls, safe work practices, employee education/training, personal protective equipment, and exposure and medical monitoring) to minimize the risk of exposure and adverse health effects.
The American Conference of Governmental Industrial Hygienists (ACGIH) TLVs were developed by committee members of this association from a review of the published, peer-reviewed literature. TLVs are not consensus standards but are considered voluntary exposure guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards" [ACGIH 2021].

Outside the United States, OELs have been established by various agencies and organizations and include legal and recommended limits. The Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung (Institute for Occupational Safety and Health of the German Social Accident Insurance) maintains a database of international OELs from European Union member states, Canada (Québec), Japan, Switzerland, and the United States. The database, available at http://www.dguv.de/ifa/GESTIS/GESTIS-Stoffdatenbank/index-2.jsp, contains international limits for more than 1,500 hazardous substances and is updated periodically.

OSHA requires an employer to furnish employees a place of employment free from recognized hazards that cause or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970 (Public Law 91–596, sec. 5(a)(1))]. This is true in the absence of a specific OEL. It also is important to keep in mind that OELs may not reflect current health-based information.

When multiple OELs exist for a substance or agent, NIOSH investigators generally encourage employers to use the lowest OEL when making risk assessment and risk management decisions. NIOSH investigators also encourage use of the hierarchy of controls approach to eliminate or minimize workplace hazards. This includes, in order of preference, the use of (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., local exhaust ventilation, process enclosure, dilution ventilation), (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection). Control banding, a qualitative risk assessment and risk management tool, is a complementary approach to protecting employee health. Control banding focuses managing broad categories of risk. Information on control banding is available at http://www.cdc.gov/niosh/topics/ctrlbanding/. This approach can be applied in situations where OELs have not been established or can be used to supplement existing OELs.

Noise

Noise induced hearing loss is an irreversible condition that progresses with noise exposure. It is caused by damage to the nerve cells of the inner ear and, unlike some other types of hearing disorders, cannot be treated medically [Meinke et al. 2022]. Approximately 25% of U.S. workers have been exposed to hazardous noise [Kerns et al. 2018] and more than 22 million U.S. workers are estimated to be exposed to workplace noise levels above 85 dBA [Tak et al. 2009]. NIOSH estimates that workers exposed to an average daily noise level of 85 dBA over a 40-year working lifetime have an 8% excess risk of material hearing impairment. This excess risk increases to 25% for an average daily noise exposure of 90 dBA [NIOSH 1998]. NIOSH defines material hearing impairment as an average of the HTLs for both ears that exceeds 25 dB at frequencies of 1 kHz, 2 kHz, 3 kHz, and 4 kHz.

Although hearing ability commonly declines with age, exposure to excessive noise can increase the rate of hearing loss. In most cases, NIHL develops slowly from repeated exposure to noise over time, but the progression of hearing loss is typically the greatest during the first several years of noise exposure [Rosler 1994]. NIHL can also result from short duration exposures to high noise levels or even from a single exposure to an impulsive noise or a continuous noise, depending on the intensity of the noise and the individual's susceptibility to NIHL [Meinke et al. 2022]. Noise exposed workers can develop substantial NIHL before it is clearly recognized. Even mild hearing losses can impair one's ability to understand speech and hear many important sounds. In addition, some people with NIHL also develop tinnitus. Tinnitus is a condition in which a person perceives hearing sound in one or both ears, but no external sound is present. Persons with tinnitus often describe hearing ringing, hissing, buzzing, whistling, clicking, or chirping like crickets. Tinnitus can be intermittent or continuous and the perceived volume can range from soft to loud. Currently, no cure for tinnitus exists.

Noise measurements are usually reported as decibels, A-weighted. A-weighting is used because it approximates the "equal loudness perception characteristics of human hearing for pure tones relative to a reference of 40 dB at a frequency of 1 kHz" and is considered to provide a better estimation of hearing loss risk than using unweighted or other weighting measurements [Murphy et al. 2022]. The dB unit is dimensionless, and it represents the logarithmic ratio of the measured SPL to an arbitrary reference sound pressure (20 micropascals, which is defined as the threshold of normal human hearing at a frequency of 1 kHz). Because the dB is logarithmic, an increase of 3 dB is a doubling of the sound energy, an increase of 10 dB is a 10-fold increase, and an increase of 20 dB is a 100-fold increase in sound energy. Noise exposures expressed in dB or dBA cannot be averaged using the arithmetic mean.

Workers exposed to noise should have baseline and yearly hearing tests (audiograms) to evaluate their hearing thresholds and determine whether their hearing has changed over time. Hearing testing should be done in a quiet location, such as an audiometric test booth where background noise does not interfere with accurate measurement of hearing thresholds. In workplace hearing conservation programs, hearing thresholds must be measured at frequencies of 0.5 kHz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, and 6 kHz. NIOSH also recommends that testing be done at 8 kHz [NIOSH 1998]. The OSHA hearing conservation standard requires analysis of hearing changes from baseline hearing thresholds to determine if an STS has occurred. OSHA defines an STS as a change in hearing threshold relative to the baseline hearing test of an average of 10 dB or more at 2 kHz, 3 kHz, and 4 kHz in either ear [29 CFR 1910.95]. If an STS occurs, the company must determine if the hearing loss also meets the requirements to be recorded on the OSHA Form 300 Log of Work-Related Injuries and Illnesses [29 CFR 1904.1]. In contrast to OSHA, NIOSH defines a significant threshold shift as an increase in the hearing threshold level of 15 dB or more, relative to the baseline audiogram, at any test frequency in either ear measured twice in succession [NIOSH 1998].

Hearing test results are often presented in an audiogram, which is a plot of an individual's hearing thresholds (y-axis) at each test frequency (x-axis). HTLs are plotted such that fainter sounds are shown at the top of the y-axis, and more intense sounds are plotted below. Typical audiograms show HTLs from −10 or 0 dB to about 100 dB. Lower frequencies are plotted on the left side of the audiogram, and higher frequencies are plotted on the right. NIHL often manifests itself as a "notch" at 3 kHz, 4 kHz, or 6 kHz, depending on the frequency spectrum of the workplace noise and the anatomy of the individual's ear [ACOM 1989; Mirza et al. 2018; Osguthorpe and Klein 1991; Schlaucha and Carneya 2011; Suter 2002]. A notch in an individual with normal hearing may indicate early onset of NIHL. A notch is defined as the frequency where the HTL is preceded by an improvement of at least 10 dB at the previous test frequency and followed by an improvement of at least 5 dB at the next test frequency.

NIOSH has an REL for noise of 85 dBA, as an 8-hour TWA. For calculating exposure limits, NIOSH uses a 3-dB time/intensity trading relationship, or exchange rate. Using this criterion, an employee can be exposed to 88 dBA for no more than 4 hours, 91 dBA for 2 hours, 94 dBA for 1 hour, 97 dBA for 0.5 hours, etc. Exposure to impulsive noise should never exceed a peak level of 140 dBA. For extended work shifts NIOSH adjusts the REL to 84.5 dBA for a 9-hour shift, 84.0 dBA for a 10-hour shift, 83.6 dBA for an 11-hour shift, and 83.2 dBA for a 12-hour work shift. When noise exposures exceed the REL, NIOSH recommends the use of hearing protection and implementation of a hearing loss prevention program [NIOSH 1998].

The OSHA noise standard specifies a PEL of 90 dBA and an AL of 85 dBA, both as 8-hour TWAs. OSHA uses a less conservative 5-dB exchange rate for calculating the PEL and AL. Using the OSHA criterion, an employee may be exposed to noise levels of 95 dBA for no more than 4 hours, 100 dBA for 2 hours, 105 dBA for 1 hour, 110 dBA for 0.5 hours, etc. Exposure to impulsive noise must not exceed 140 dB peak noise level. OSHA does not adjust the PEL for extended work shifts. However, the AL is adjusted to 84.1 dBA for a 9-hour shift, 83.4 dBA for a 10-hour shift, 82.7 dBA for an 11-hour shift, and 82.1 dBA for a 12-hour work shift. OSHA requires implementation of a hearing conservation program when noise exposures exceed the AL [29 CFR 1910.95].

An employee's daily noise dose, based on the duration and intensity of noise exposure, can be calculated according to the formula: Dose = 100 x (C1/T1 + C2/T2 + ... + Cn/Tn), where Cn indicates the total time of exposure at a specific noise level and Tn indicates the reference exposure duration for which noise at that level becomes hazardous. A noise dose greater than 100% exceeds the noise exposure limit.

To calculate the noise dose using NIOSH criteria, the reference duration (Tn) for each time period must be calculated using the following formula:

$$T(\text{minutes}) = \frac{480}{2^{(L-85)/3}}$$

where L = the measured noise exposure level for each time period.

To calculate noise dose using OSHA criteria, the reference duration (Tn) for each time period must be calculated using a slightly different formula:

$$T(\text{minutes}) = \frac{480}{2^{(L-90)/5}}$$

where L = the measured noise exposure level for each time period.

Appendix C: Methods

Noise Dosimetry

We measured full-shift personal noise exposures using Quest Technologies NoisePro® DLX noise type-2 dosimeters. For noise measurements, each dosimeter was attached to the wearer's belt and a 0.335-inch random incidence microphone was fastened to the wearer's shirt at a point midway between the ear and the outside of the shoulder. Windscreens were placed over the microphones to reduce or eliminate artifact noise, which can occur if wind from a fan blows across an unprotected microphone, or something bumps into an unprotected microphone. We set up the dosimeters to collect data using different settings to allow comparison of noise measurement results with the three different noise exposure limits referenced in this health hazard evaluation report (Table C1). The dosimeters integrated noise at a 50-hertz (Hz) sampling rate averaging results every second during monitoring. Therefore, each dosimeter recorded approximately 28,800 individual 1-second averaged noise exposure measurements for a full 8-hour shift. During measurements, noise levels below the threshold level were not integrated by the dosimeter for accumulation of dose and calculation of TWA noise level. The dosimeters averaged noise levels every second. We calibrated the dosimeters before and after the measurement periods according to the manufacturer's instructions.

Table C1. Dosimeter settings

Exposure limit parameters	OSHA AL	OSHA PEL	NIOSH REL
Response	Slow	Slow	Slow
Exchange rate	5	5	3
Criterion level	90	90	85
Threshold	80	90	80

We measured area sound levels at several workstations or pieces of equipment using a Quest Technologies SoundPro® Model SE/DL sound level meter. The instrument was equipped with a ½-inch free-field Type 2 electret microphone and measured noise levels from 10–140 dB. The microphone had a frequency response range (± 2 dB) from 20 Hz–17 kHz. During measurements, the sound level meters were either hand-held or mounted on a tripod at a height of approximately 5 feet.

We downloaded noise measurement data collected using dosimeters and sound level meters to a personal computer for interpretation with QuestSuite® Professional II for Windows® computer software. All noise monitoring equipment were calibrated before and after use according to the manufacturer's instructions.

Impact Noise Measurements

We measured impact noise at forge hammers, upset presses, shear presses, and shot blast units. We used a National Instruments model 9162/9215 USB data acquisition board to acquire impact noise data at a 100 kHz sampling rate (i.e., 100,000 samples per second). We used Brüel and Kjær 0.25 inch microphones (model 4136) for impact noise measurements. A signal conditioner model Nexus provided power for the microphones. During data collection the microphones were supported on boom stands and oriented in grazing incidence (90-degree angle from the noise source) at the nominal hearing zone, which was 5 to 6 feet high. Two noise measurements were simultaneously taken at each location. One measurement was collected near the position of the worker and a second measurement was taken approximately 6 feet from the worker. Extension cables were used as necessary to accommodate distance from the microphones to the signal conditioner. The signal conditioner, laptop, and data acquisition chassis were set on a mobile cart.

Time records were acquired and streamed to a binary format and later reprocessed. The microphones were calibrated each morning before measurements were made with a Brüel and Kjær piston phone calibrator (model 4228). Noise measurements and recordings were made for each individual part. The file format for recordings was a binary single precision floating point format with units of Pa for the sound data.

NIOSH engineers used MATLAB® by Mathworks (Natick, NH) to write several programs to analyze and describe impulsive and continuous sound. A program named Impulsive Noise Meter, identified each peak, placed the peak in a 0.5-second time window with 25% of the time before the peak, and then calculated the impulsive noise metrics. The metrics were stored in a MATLAB® structure along with descriptive information. In addition to the impulsive noise analysis, a continuous analysis of the data was accomplished with the MATLAB® program named Continuous Sound and Vibrations. This program created 5-second time windows and then calculated the continuous sound and vibrations metrics and stored the metrics in a MATLAB® data structure. For each work area where we measured impulsive noise, another MATLAB® program, Main_Metrics, was used to combine the metrics, calculate descriptive statistics, and make summary data plots.

Analysis of Audiometric Test Records

We received an electronic database of audiometric test records for 104 current or former forge shop employees. We removed personal identifiers and then assigned new employee numbers sequentially. To ensure quality and accuracy of the audiograms for analysis, an experienced audiologist used previously established NIOSH audiometric quality assurance screening guidelines [Franks 1999] to identify and remove audiograms that were incomplete or had audiometric patterns indicating hearing loss could have resulted from non-occupational factors or inaccurate audiometric thresholds, as detailed below. Following screening, we analyzed the remaining audiometric data to identify hearing loss trends and compare NIOSH and OSHA compliance metrics.

NIOSH audiometric quality assurance guidelines for screening audiograms:

1. General rules

   a. All records containing only one audiogram must be deleted.
   b. All audiograms containing a "No Response" threshold must be deleted.
   c. An audiogram must be deleted if it contains a threshold that differs by 50 dB or more from the thresholds at both adjacent frequencies.

   Note: At the highest and lowest test frequencies, an audiogram should be deleted if the threshold differs by 50 dB or more from the one adjacent frequency.

2. Intra-aural difference rules
   An audiogram must be deleted if there is a difference in threshold between ears at the same frequency of 25 dB or more at 0.5 kHz and 1 kHz or 40 dB or more at 2 kHz, 3 kHz, 4 kHz, 6 kHz, or 8 kHz.

3. Negative slope rules
   An audiogram must be deleted if the threshold at 0.5 kHz in either ear is 15 dB or more poorer than the threshold at 1 kHz in the same ear or if the threshold at 1 kHz in either ear is 10 dB or more poorer than the threshold at 2,000 Hz in the same ear, unless all three of the following conditions are met:
   a. The thresholds at 0.5 kHz, 1 kHz, and 2 kHz in the ear in question are all 20 dB or better.
   b. The threshold at 0.5 kHz is better than or equal to the threshold at 1 kHz in the ear in question.
   c. The threshold at 1 kHz is no more than 10 dB poorer than the threshold at 2 kHz in the ear in question.

4. 15-dB shift rules

   Rule 1: Do not include audiograms marked for deletion.
   Each audiogram is compared to the valid audiogram immediately preceding it. If the immediately preceding audiogram has been deleted, the last retained audiogram is used for comparison.

   a. Unconfirmed decrease in hearing ability

      An audiogram must be deleted if it differs from its comparison audiogram at any frequency in either ear by 15 dB or more and the new threshold is not confirmed within ±10 dB on the next valid audiogram.
      Note: If the threshold on the confirmation audiogram differs by more than 10 dB in the same direction as the shift and this change is confirmed on the majority of future audiograms, the audiogram should be retained.

   b. Confirmed improvement in hearing ability

      Note: Because we are interested in permanent threshold shifts, if hearing improves from a previous audiogram and this improvement is confirmed in the next audiogram, then the initial audiogram in this sequence must be marked for deletion.

The exception in this rule is based on not wanting to discard an audiogram that shows hearing loss in another frequency; it is an override rather than an exception.
Note: This rule addresses learning and only applies to the initial audiograms.

The first audiogram in a set must be deleted if a threshold at any one frequency in either ear improves by 15 dB or more on the next valid audiogram, and the improved threshold is confirmed (±10 dB) unless a threshold at another frequency in either ear worsens and is confirmed. In this case (i.e., some thresholds improving and some getting poorer between the first and second audiograms with confirmation on the next test), both audiograms should be retained.

Example: A frequency 2 kHz in left ear: first reading is 30 dB, second reading is 10 dB (this is a 20 dB improvement and more than meets the first criterion)

Possible Outcome 1:
Third reading is 20 dB. This is the worst reading that can confirm the improvement within ±10 dB. The audiogram would be deleted unless there was evidence of hearing loss at a different frequency.

Possible Outcome 2:
Third reading is 25 dB. This reading does not confirm the improvement within ±10 dB; it is 15 dB different from the improved reading. Thus, the audiogram would not be deleted even though this reading still shows some improvement.

This rule only applies to improvements in threshold between the first two valid audiograms. If all threshold shifts are in the poorer direction, and this worsening is confirmed, the initial audiogram will still be considered valid, and the decreased thresholds will be considered a threshold shift. It will be assumed that the initial audiogram with the better threshold was obtained under better conditions than subsequent audiograms, and the initial threshold will be considered a true threshold. If there are improvements and decreases between the first two valid audiograms, it will be assumed that these changes represent true changes in hearing and are not due to environmental factors, and both tests will be retained.

If thresholds continue to improve on subsequent audiograms (i.e., thresholds improve from the first audiogram to the second, and again from the second audiogram to the third, etc.), delete subsequent audiograms until the thresholds remain stable or at least one threshold becomes poorer. This rule only applies to audiograms at the beginning of a record. Once thresholds stabilize or begin to worsen, later audiograms which show improvements should be retained (provided the improvements are confirmed).

Rule 2: To exclude audiograms marked for deletion, it is necessary to iterate these tests until no more audiograms are deleted.

A shift on one audiogram must be confirmed by the next valid audiogram. If an audiogram that confirmed a threshold shift is later determined to be invalid, the threshold shift must be reconfirmed using the next valid audiogram. If the next valid audiogram does not confirm the shift, the audiogram in question must be deleted.

Exception: If the confirmation audiogram is the last audiogram in the series that is being deleted, the shift will still be considered confirmed. If several consecutive audiograms are deleted at the end of a record, any shifts on the audiogram immediately preceding them will still be considered confirmed, if indeed they were considered confirmed before the audiograms were deleted.

Example: Audiograms A B C.......V W X Y Z
Audiogram W shows shift relative to Audiogram V.
Audiogram X confirms the shift; Audiogram W is retained.
Audiogram X shows shift relative to Audiogram W.
Audiogram Y does not confirm shift; Audiogram X is deleted.
Audiograms Y and Z are similarly deleted.
Audiogram W is still retained.

Conversely, an audiogram that was deleted because of an unconfirmed shift should be restored if the confirmation audiogram (i.e., that audiogram that showed the shift to be unconfirmed) is later determined to be invalid, and the next valid audiogram confirms the previously unconfirmed shift.

Example: Audiograms A B C D E...
Audiogram B shows shift relative to Audiogram A.
Audiogram C does not confirm shift; delete Audiogram B.
Audiogram C shows shift relative to Audiogram A.
Audiogram D does not confirm shift; delete Audiogram C.
Compare Audiogram A and B again; Audiogram D confirms shift.
Restore Audiogram B.

The last audiogram in a series must be deleted if it shows a shift relative to the last valid audiogram, because there is no future audiogram to use to confirm the threshold change.

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