Applying System Safety
ZOO WORKER DI
EXPOSURE PREV

By Emma Villarreal, Cheri L. Marcham, Michael O'Toole and Bart Eltz

AS OF MARCH 2023, 238 total zoological parks and aquariums have been accredited by the Association of Zoos and Aquariums (AZA, n.d.) within the U.S. and internationally. Thousands of smaller, nonaccredited zoos can be found globally as well. More than 1,200 professionally managed zoos and aquaria are in operation throughout the world (Brown, 2004). Zoos strive to protect wild animals through education, research and conservation efforts. Zoos place various species on exhibit in publicly viewable enclosures primarily during working hours. When the facility is open, staff may routinely host petting zoo events or supervise "touch tanks," allowing the public to feed or handle certain animals, which may include domestic farm animals and exotic species. These experiences encourage public engagement with the zoo and allow for zoo workers to share knowledge about the animals and conservation efforts.

Zoos also manage holding rooms or tanks not displayed to the public. Larger animals such as big cats, elephants and giraffes may be trained to retreat to these settings for rest at night when the facility is closed. These holding units may also be used to house animals full time, such as those too young to be exhibited with other species, animals with health concerns or in need of veterinary care, those requiring lower-stress environments, or newly transferred animals that must be quarantined separately from others. While the public is denied access to these areas, staff still interact with the animals in the holding environments. Animals may stay in the holding area until a department manager or zoo veterinarian determines that they are fit to join the publicly viewed exhibits.

According to Section 5(a)(1) of the OSH Act (1970), employers must ensure a safe working environment for all workers. Employers must address hazard categories such as general housekeeping, slips, trips and falls, equipment operation and maintenance, and electrical hazards. The zoo may additionally have emergency response plans in place for environmental or zoo-housed animal emergencies such as natural disaster, fire or enclosure escape.

The Zoo and Aquarium All Hazards Partnership (ZAHP, 2017a) agrees that staff, responder and public safety must be the top priority in safety plans, as animals supported by zoos are considered property of the zoo. A zoo may employ an occupational health and safety management system to appropriately evaluate potential workplace hazards and their sources as well as to fulfill the OSHA requirement. An occupational health and safety management system can continually enhance the safety and health performance of an establishment. In turn, worker and public perception may improve, and communities may continue to support zoos that emphasize safety (ZAHP, 2017a).

Zoos may encounter various unique hazards that necessitate risk management efforts to best protect the health of the animals and the safety of visitors and workers. Staff are at a higher risk of contact with hazards than visitors, as they are in closer and more frequent contact with potentially dangerous or ill animals and their containment areas. Stricter security measures or safety protocols may be required for those handling or transporting higher risk animals or those who may come in contact with waste and potentially hazardous materials. Animal species that are larger in

KEY TAKEAWAYS

- **While several professional agencies have already explored the causes, consequences, and preventive measures for occupational hazards such as pathogen and zoonosis exposure in animal work facilities through traditional biosafety risk assessment procedures, the authors explore the novel application of system safety in nontraditional and unconventional environments.**
- **In this evaluation, several commonly used system safety techniques are compared for their ability to proactively protect against exposure to occupational diseases in a case study using a zoological park environment as a nonconventional setting.**
- **Ultimately, fault-tree analysis (FTA) was deemed an efficient model for disease management in zoological parks. This process is combined with the hierarchy of controls to propose more effective hazard and risk management practices, which should reduce the likelihood and gravity of pathogens and zoonoses in a zoo work environment.**
- **This article provides a comprehensive review of the benefits and limitations of four system safety techniques and uses practical examples from a zoo worker's perspective for FTA application.**

Analysis to SEASE ENTION

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size, venomous or dangerous in other ways may pose greater risk to workers, but visitors typically remain at lower risk than employees for most zoo hazards if proper exhibit and barrier architecture and engineering are established. Barriers may include wet moats, dry moats, fences and glass barriers to appropriately distance the public from the enclosures. Different safety measures should apply for interactive events in which the public can be in contact with certain animals.

Exposure to pathogens and zoonotic diseases is a potentially high-severity occupational risk for zoo employees, as various work activities can put them in direct contact with harmful organisms. Such work activities include cleaning exhibits and public spaces, administering medication to animals, providing veterinary care for domestic and exotic species, preparing food for and feeding animals, and performing chemical tests on aquarium water. Disease exposure may occur through direct or indirect contact, vectors, and food and water sources. With these multiple exposure routes and continuous close contact with animals during work activities, zoo staff must always be conscious of risks. In contrast, the highest risk activity for the public may be handling animals during petting zoo or touch tank events, as visitors otherwise remain at a relatively large distance from the animals.

Contact with pathogens and zoonotic diseases by zoo staff and the public can lead to detrimental health effects for individuals, as well as various direct and indirect costs for zoo organizations. For instance, in 2019, eight workers at the Point Defiance Zoo in Washington state tested positive for latent tuberculosis (TB), most likely contracted from elephants, which frequently carry TB (Majumdar, 2020). Latent TB is not contagious and does not present symptoms itself, but it can develop into active and infectious TB and therefore requires medical diagnosis and treatment (CDC, 2011). Without proper medical care, TB can lead to death. While the AZA recognizes zoonotic disease risks such as those from TB, a detailed phase-out plan has yet to be constructed. Therefore, a need exists for more stringent proper disease risk management to further reduce system failure or human error likelihood, ensure worker safety and health, reduce costs, and meet the requirements of the OSH Act.

System Safety Application to Occupational Exposures

While there are known methods of risk assessment for animal biohazards in the research environment (CDC & NIH, 2020), there are no guidelines purely for risk assessment and management in zoo settings. The purpose of system safety analysis techniques is to identify hazards and their potential risk and consequences before an incident occurs as well as to manage risk by ensuring that the proper controls are in place. The key to successful implementation and use of system safety techniques is incorporation of multidisciplinary action. This permits collaboration across multiple professions to mitigate or eliminate an identified hazard. By connecting this system safety practice and the hierarchy of controls (NIOSH, n.d.), employers can be encouraged to consider novel risk management techniques that likely reduce the probability and severity of the hazard. Hence, the present study aimed to apply system safety analysis techniques in the novel environment of zoos, showcasing the effectiveness of utilizing such techniques in any context while emphasizing the power of using such tools.

The first research question: For zoo worker exposure to pathogens and zoonotic diseases, which system safety analysis technique should be applied to most effectively investigate both potential system flaws and human errors? Many diverse models could be deemed appropriate risk assessment techniques for determining sources of zoo worker pathogen and zoonosis exposure and analyzing potential consequences of these contacts. Examples include fault-tree analysis (FTA), failure modes and effects analysis (FMEA), bow-tie method, and hazard and operability (HAZOP) analysis. Applicability of these system safety techniques to specific workplace hazards may vary based on the model's own unique abilities to assess potential system faults and human errors. Thus, the different techniques and each of their components when applied qualitatively should be compared to determine which model is most suitable for this certain hazard.

The second research question: How may the selected model be synthesized with the hierarchy of controls and scholarly literature to ultimately prevent key exposure routes to reduce work-related illness cases and enhance working conditions? To better safeguard the safety and health of workers from these hazards, data collected through the designated system safety approach must be understood and applied by zoo facilities to lead to efficient hazard control evaluation. Once the hazard controls are updated, pre- and posttreatment risk magnitudes can then be compared with the selected system safety technique to determine whether further safety measures are necessary (Voicu et al., 2018). Through this comprehensive study, the OSH Act and safety culture should be supported, and the academic and zoo safety fields may apply this information and continue to evolve. Upon preventing and mitigating key exposure routes, work-related illness cases within the zoo industry may decline, and working conditions, worker morale and public perception may improve.

TABLE 1
PATHOGENS & ZOONOSES EXAMPLES, SYMPTOMS

Various pathogens and zoonoses and their common symptoms in human cases are presented to help zoos better understand the severity of workplace pathogen and zoonosis exposure and how important it is to implement a successful disease management program.

Type of pathogen or zoonosis	Disease examples	Common symptoms
Bacterial	Lyme disease, *E. coli* infection, salmonellosis, anthrax, tuberculosis and bordetellosis	Fever, abdominal pain, gastrointestinal irritation with vomiting and diarrhea, joint pain, respiratory complications, skin rash. Anthrax, tuberculosis and bordetellosis may result in respiratory complications.
Viral	Rabies, avian influenza, severe acute respiratory syndrome (SARS), Ebola, West Nile virus	Fever, muscle pain, headache, chills
Parasitic	Cutaneous larval migrans, cryptococcosis, trichinellosis	Abdominal pain and gastrointestinal irritation with nausea, vomiting, diarrhea
Mycotic and fungal	Ringwork infection, blastomycosis, and histoplasmosis	Fever, cough, skin lesions
Rickettsial	Query fever, or "Q-fever," Queensland tick typhus	Fever, headache, cough, rash
Chlamydial	Psittacosis, chlamydiosis, enzootic abortion	Abdominal pain, pelvic inflammation. Chlamydiosis can result in tubal factor infertility. Enzootic abortion can trigger spontaneous abortion.
Protozoal	Leishmaniasis, toxocariasis, giardiasis, balantidiasis	Fever, nausea, diarrhea. Balantidiasis can result in intestinal ulcerations.
Acellular, nonviral pathogenic agents (prion)	Bovine spongiform encephalopathy, Creutzfeldt-Jakob disease	Bovine spongiform encephalopathy—or mad cow disease and known in humans as Creutzfeldt-Jakob disease—often leads to seizures and memory loss.

Note. Adapted from "Zoonotic Diseases: Etiology, Impact, and Control," by T. Rahman, A. Sobur, S. Islam, S. Ievy, J. Hossain, M.E. El Zowalaty, T. Rahman and H.M. Ashour, 2020, *Microorganisms, 8*(9), pp. 1-34 (https://doi.org/10.3390/microorganisms8091405).

Occupational Hazards: Exposure to Pathogens & Zoonotic Diseases

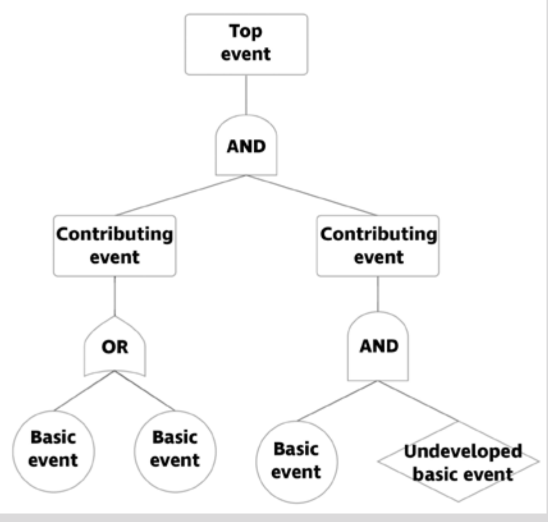
As noted, a prominent worker hazard in zoo facilities is exposure to pathogens and zoonotic diseases. To determine proper disease management practices and to successfully construct and execute safety protocols for this hazard, all possible exposure routes for these diverse pathogens and zoonoses must be explored. If hazard control measures are lacking, then zoo staff may have a high probability for contact with these biological hazards through the various exposure routes. To better recognize the potential impacts of pathogen or zoonosis exposure, the severity of the health effects linked to infection must also be understood. With inefficient disease prevention and control programs, not only may workers' health be at risk, but businesses can also be adversely affected by work-related illnesses through direct and indirect effects.

Pathogens are microbes that cause diseases in other organisms (Casadevall & Pirofski, 2002). Pathogen exposure routes include inhalation, ingestion, injection, direct contact and vectors. Vectors are living organisms that transmit an infectious agent, like a pathogen, to another individual. Common vectors include ticks, fleas, flies and mosquitoes, but animals that have the potential to transmit pathogens to humans are also vectors.

Zoonotic diseases are diseases or infections that can be transmitted between vertebrate animals and humans (Rahman et al., 2020). Zoonoses may result from

FIGURE 1
FTA TEMPLATE

The top-down approach of the FTA model is presented. The top level represents the undesired event. With the hazard identified, primary causes for this hazard are detailed, and effects due to exposure to this hazard can be explored.



bacteria, ectoparasites, fungi, helminths, prions, protozoa or viruses (Sim et al., 2022). Zoonotic diseases may spread between humans and vertebrate animals through direct and indirect transmissions via exposure routes such as inhalation, ingestion, injection, dermal absorption and vectors. The most common exposure pathways of zoonoses passing from animals to humans involve droplets, bites or vectors (Rahman et al., 2020). Foodborne pathogens and zoonoses may be correlated, as handling or ingesting infected food or water increases risk of contact with both pathogens and zoonoses. As zoo staff prepare animal food each workday, their risk for disease exposure is increased (Shahid & Daniell, 2016).

Zoonoses may also develop or reemerge through contact with wild animals (Rahman et al., 2020). Due to ever growing populations and habitat interference, emerging infectious diseases are on the rise. Emerging infectious diseases are newly developed diseases that can be transmitted as pathogens or zoonoses. In fact, zoonoses make up an estimated 60.3% of emerging infectious diseases and about 71.8% of these originate from wildlife (Chomel, 2009; Rahman et al., 2020).

Since zoo staff often interact with both captive and wild animals for conservation efforts, strict precautionary measures against pathogen and zoonosis exposure are vital to best safeguard worker safety and health. The zoonotic pathogen's genus, natural hosts, intermediate hosts, incubation period, signs and symptoms, and epidemiology should be understood for swift identification and accurate treatment. Also, because evolving definitions are always possible, continued studies and new evidence of pathogens and zoonoses are necessary to maintain up-to-date descriptions and safety programs.

Table 1 details examples of bacterial, viral, parasitic, mycotic and fungal, Rickettsial, chlamydial, protozoal, and prion zoonoses and their common symptoms. The table also describes more severe potential health consequences caused by specific pathogens and zoonoses. Symptoms for each zoonosis category are not limited to those listed. Additionally, immunosuppression can lead to further infection susceptibility, and even death by zoonoses (Sims et al., 2022). When an individual comes in contact with one of these diseases through work processes and tests positive for a disease or experiences symptoms, these events may be considered OSHA-recordable incidents. An illness qualifies as an OSHA-recordable work-related illness if the worker requires days away from work or altered work practices, seeks medical treatment beyond first aid, experiences fainting, or if a fatality results (OSHA, 2001).

Individuals in occupations that involve regular animal handling, such as zoo workers, have a higher probability of encountering pathogens and zoonoses due to their frequent contact with wild species. Kinnunen et al. (2022) reviewed a study in 2009 with 306 veterinarian participants and compared the findings to another study performed in 2016 with 262 veterinarians. In the 2009 study, only about

FIGURE 2
FTA APPLICATION EXAMPLE

An example of how the FTA model may be applied. The FTA demonstrates how the probability of a top event, or sump pump failure in this hypothetical instance, can be calculated based on the probabilities of the basic and intermediate events occurring and the "and" and "or" gates determined.

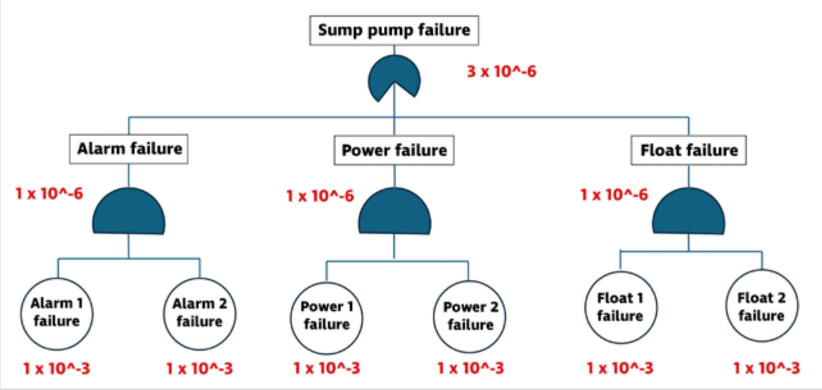
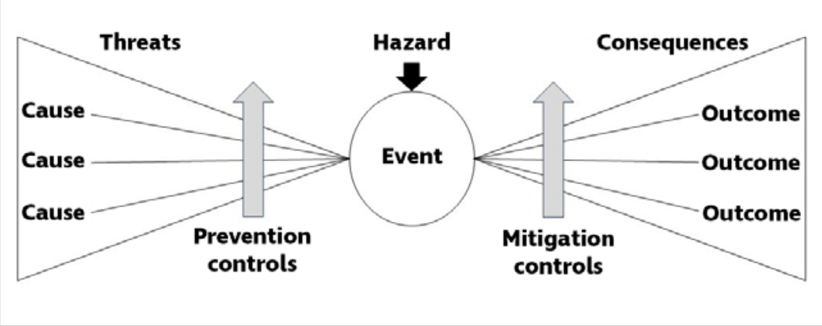


FIGURE 3
BOW-TIE DIAGRAM

The elements of the bow-tie method. With the event identified, causes and outcomes of the hazard may next be assessed. The system also permits the analysis of preventive controls for causes to prevent hazard exposure and recovery mitigation controls for outcomes to minimize effects.



8.2% fully agreed with the claim “I have good knowledge of zoonoses and their prevention,” and this number rose to only 10.3% in the 2016 study (Kinnunen et al., 2022, p. 81). Consequently, the veterinarians reported inconsistent compliance with disease management protocol throughout the years. Rather than properly wearing gloves at all times, in the 2009 study, just 82.4% of the veterinarians reported wearing gloves when examining infected wounds of small animals, and 67.9% of the veterinarians wore gloves when examining infected wounds of larger animals such as horses. Glove usage in the 2016 study for smaller animals and horses then climbed to 84.9% and 79.2%, respectively. Although usage increased, the data show that there is still need for improvement with training and compliance of disease management plans (Kinnunen et al., 2022).

Even with disease management plans in place at veterinary facilities, more than 90% of veterinarians reported exposure to zoonotic pathogens while at work, and 15% of the individuals had contracted a zoonotic disease (Kinnunen et al., 2022). Moreover, approximately 80% had accidentally poked themselves with a needle that previously stuck an animal. Nearly 85% of veterinarians reported animal bites from both smaller and larger animals, where 13.5% of these bites required the person to take sick leave (Kinnunen et al., 2022).

Molineri et al. (2013, p. 286) note that “veterinarians [may] underestimate the impact of zoonoses and may have a passive attitude regarding their own health.” This indicates that steps must be taken to show those who work with animals the serious nature of pathogen and zoonosis illnesses and how lack of safety procedures or disregard of these protocols can increase risk of severe illness and OSHA-recordable incidents. This demonstrates the importance of workplace disease management, especially for workers such as zoo staff who continuously handle wild animals, the increased exposure risk for these professionals, and how greater awareness is needed in the field.

With expanded knowledge of the potential exposure routes and health consequences of worker exposure to these biological hazards, zoos can recognize the importance of conducting routine, thorough workplace risk assessments and administering strict hazard control measures. Likewise, with the sources and health costs of the hazard now known, frequently utilized system safety techniques can be compared to later determine which model is the most applicable for this workplace hazard.

System Safety Analysis Technique Selection Process

When performing a hazard analysis, various techniques from system safety may be considered. Application of system safety methodology can aid in hazard identification and risk management. With pathogen and zoonosis exposure identified, the most appropriate system safety model for zoos to apply for this particular risk may be explored. Once an appropriate system safety technique has been employed, the hazards and risk are better understood, and control measures can be initiated. Each technique has distinguishing advantages and drawbacks compared to the other processes.

Fault-Tree Analysis

The purpose of fault-tree analysis (FTA) is to highlight potential root causes of workplace mishaps and determine the probability and severity of the effects through a deductive, top-down approach (Ericson, 2015; Manuele, 2020). This method may be used to qualitatively and quantitatively evaluate complex systems, and this model assesses the correlation between multiple system failures or human errors to determine practical preventive measures. FTA helps articulate how a sequence of lower-level events can come together and lead to the top event. It is most commonly applied to preventive actions, identifying potential failure sources before an event occurs (Manuele, 2020). FTA demonstrates how particular operations within systems can fail, and it may be utilized to distinguish the best risk management processes as well as designate a risk rate to a failure. Analysis of existing safety protocols and identification of their successes and deficiencies can also be accomplished through FTA, and updates are reported fairly simply (Ericson, 2015; Manuele, 2020).

Specifically, FTA identifies conditions or combinations of conditions that may fail and trigger a distinct adverse effect (Manuele, 2020). Based on the standardized method developed by H.A. Watson of Bell Laboratories, FTA provides a visual model (Figure 1, p. 26), often developed using software (Ericson, 2015), that uses symbols and shapes to show how different events and conditions can lead to a system failure.

Figure 1 (p. 26) provides a simplified example of how a typical FTA is constructed. Rectangles, circles and

FIGURE 4
FTA FOR ZOOS: BASIC EXAMPLE

The FTA model for hazard of pathogen and zoonosis exposure in zoo workplaces begins here and continues in subsequent figures.

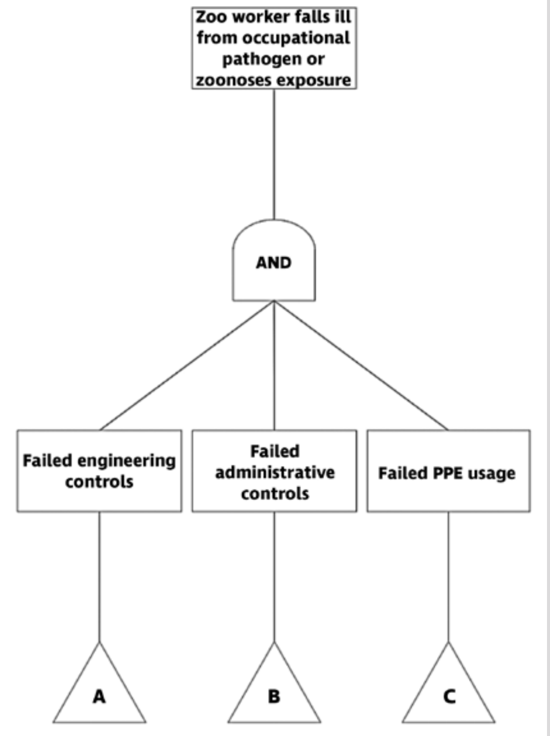


FIGURE 5

FTA FOR ZOOS: FAILED ENGINEERING CONTROLS

The failed engineering controls intermediate event.

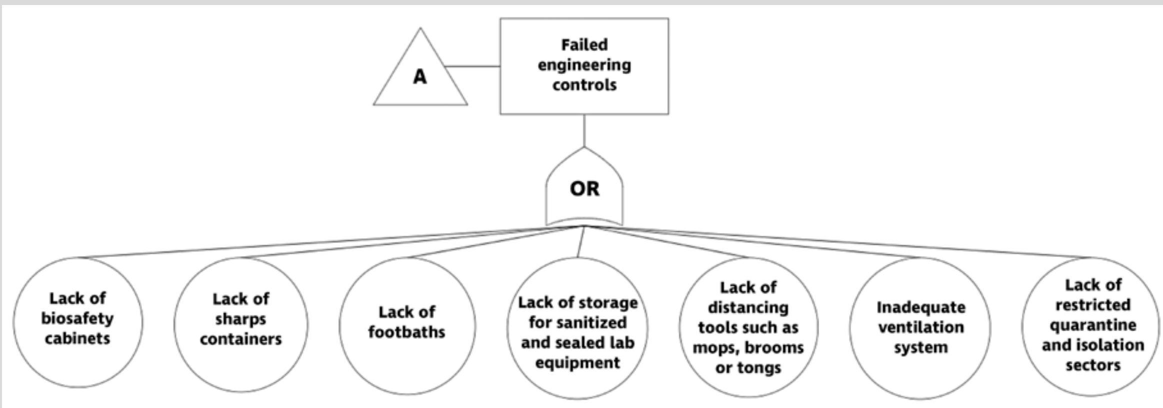
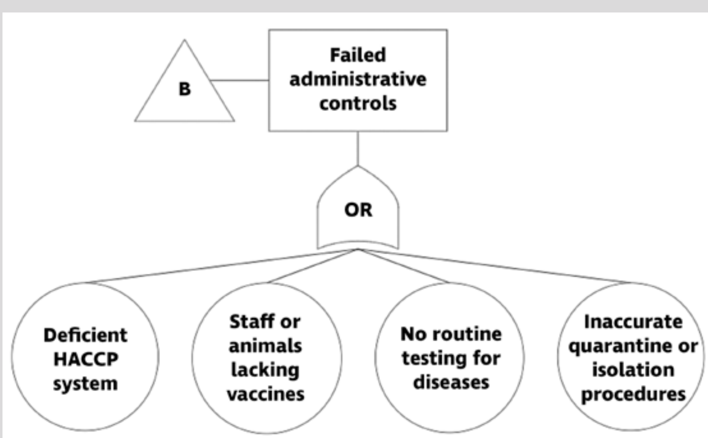


FIGURE 6

FTA FOR ZOOS: FAILED ADMINISTRATIVE CONTROLS, PART 1

Part 1 of the failed administrative controls intermediate event.

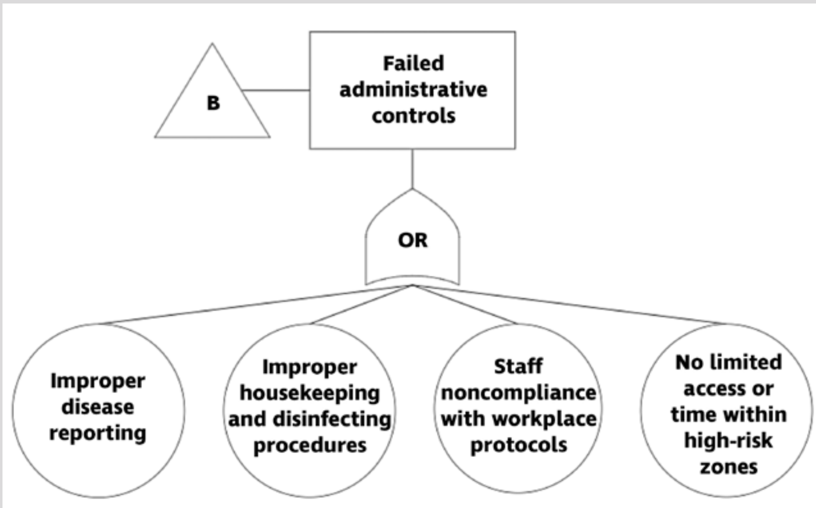


diamonds represent events or specific occurrences that can go wrong in a system. Rectangles characterize top or intermediate failure events, and the top level represents the undesired event (Ericson, 2015). Undesired events include employee injuries or fatalities, equipment failures, product or process defects, and other potential outcomes (these are not hazards). Next, intermediate events are also referred to as the primary causes. The intermediate events are triggered by other events that are even lower, known as basic events. Basic events are portrayed by circles and are the most elemental factors that have some likelihood of being part of the causal pathway that results in the incident. Lastly, diamonds represent undeveloped events, where information is unavailable and prevents the failure from being a developed event. The different transfer symbols, or gates, show how these events are connected logically. The "and" gate requires all events connected to it to occur to move up to the next level. The "or" gate allows for any of the events connected to it to move up to the next level. These symbols help analysts understand the causes and often the likelihood of system failures by deconstructing complex relationships into simpler events. By using these symbols, analysts can identify potential weaknesses and plan ways to improve the system's reliability and safety.

Whenever feasible, quantitative data regarding reliability, safety or quality of components of the system should be obtained. The safety professional should consider the root causes when identifying the basic events in the FTA to successfully incorporate hazard prevention methods, avert system failures and deter escalation. For example, engineering control failures may stem from a lack of or incorrect engineering system selection or improper installation. These processes connect to administrative controls, which should outline engineering control expectations in the policies and procedures. Administrative control root causes tie back to policies and procedures as well as subsequent staff training and continued education. PPE failures may result from staff using an incorrect decision tree, where administrative processes were not followed. This data helps assign probability values for the occurrence of the basic events, which can then be used to calculate the probability of the intermediate events and top event happening for the specific workplace. Figure 2 (p. 27) depicts a simple FTA for a sump pump system with three subsystems, each with a probability of failing one in 1,000 operations. The redundancy of the subsystems requires both subsystem components to fail (the "and" gate) to move up to the next level. These

FIGURE 7
FTA FOR ZOOS: FAILED ADMINISTRATIVE CONTROLS, PART 2

Part 2 of the failed administrative controls intermediate event.



known probabilities result in a one in 1 million chance of that subsystem failing. In this example, only one leg of the FTA needs to fail (the "or" gate) to create a system failure. This results in three failures in 1 million operations.

Ericson (2015) argues that FTA may be considered beneficial for pathogen and zoonosis exposure for zoo workers as it considers both potential causes and effects. Although the complex tool considers external events to productively identify potential hazard sources, partial failures may not be addressed and could still lead to workplace incidents and related costs. FTA also requires an experienced analyst and is time consuming and expensive, and missed sources and consequent work-related illnesses could further increase these expenses.

Failure Mode & Effects Analysis

Failure mode and effects analysis (FMEA) is a systematic approach for understanding and analyzing potential failures in a system and is predominantly used in the manufacturing industry (Manuele, 2020). FMEA takes a more qualitative and inductive, or bottom-up, approach than FTA. FMEA determines how equipment of a system might fail and measures the effects of these failures on the system.

FMEAs have historically been completed using worksheets, which can vary in complexity; this intricacy depends on the system and who is performing the analysis (Ericson, 2015), although software is now available to facilitate the process. The worksheet typically lists components, including a reference number, details of the function or process, and potential failure mode. The failure mode concerns what has or might go wrong in the system, and each function or process may have multiple failure modes. The FMEA worksheet considers potential causes for each of the failure modes and potential effects of the failure modes on areas such as the subsystem, assembly and subassemblies, as well as their impact on the system. The severity of the potential failure impact on the user and probability of the failure mode taking place are quantified. FMEAs even estimate a detection ranking, which considers how easy it is to detect faults in a system and evaluates existing controls and their abilities to reduce failure impacts.

The severity ranking, probability of occurrence, and detection rankings for the potential failures are each rated from one to 10, with one classifying the lowest influence and 10 representing the highest impact (Manuele, 2020). Next, taking these rates into account, FMEA calculates the risk level—or risk priority number—by multiplying the severity, probability and ease of detection values. The employer may prioritize mitigation actions, which are recommended in the FMEA worksheet, of potential failures with greater risk priority numbers. The FMEA worksheet provides a section to highlight responsibilities and expectations for these mitigation actions. Once the hazard controls are updated and complete, the system performance may be reassessed. Over time, further FMEA investigations can help predict potential system failures, and the probability and severity of events can be more accurately estimated.

Like FTA, FMEA identifies hazards but also determines the potential failure of some part of a system, the mode of failure, and the impact on that part of the system, assesses its potential causes, and focuses on the effects of the failure (Ericson, 2015). But unlike FTA, FMEA does not analyze the whole system but instead notes potential failures for each system component. Instead of considering failure mode combinations like FTA, FMEA only reflects on single component failures and assesses the range of their impacts on the system. Also, FMEA does not consider external events or undeveloped failures and is more resource-intensive than FTA.

Bow-Tie Method

The bow-tie method is a qualitative system safety visual tool that elucidates how incidents can be prevented through proper application of hazard controls, or barriers, yet multiple barrier failures can lead to a major incident (Voicu et al., 2018). Because of its simplistic design, this method provides an advantage for system safety communication and understanding for workers of all levels (de Ruijter & Guldenmund, 2016). The bow-tie method may even be used to train workers on safety and show why it is vital to properly follow protocols.

The bow-tie method reveals how a hazard may lead to an undesired event as well as the threats and consequences for such an event. As shown in Figure 3 (p. 27), the center of the bow-tie diagram represents a hazard, or a factor that has potential to cause a system harm (Voicu et al., 2018). The left side signifies threats, or all the potential causes for the hazard to lead to the top event. The right side signifies consequences, or all the potential outcomes in the form of harm or damage that results in the top event. Any threat may trigger the top event, and the event may produce any of the consequences.

Barriers can prevent or mitigate the threats and consequences (Voicu et al., 2018). Barriers on the left of the bow tie are known as preventive barriers, which prevent the top event from occurring. Barriers on the right are known as mitigative barriers, which do not stop the top event from occurring but reduce its consequences to fail-safe. Note that barriers have the possibility of failing, but the bow-tie method may examine any possible barrier faults that could lead to exposure of the hazard. This method helps visualize a given hazard, its causes and consequences, and barriers for these sources and outcomes that can reduce risk or hazard severity.

Benefits of the bow-tie method include its ability to communicate hazard causes and effects, simplify complex risk scenarios, and help identify safety vulnerabilities in work processes (Voicu et al., 2018). Risks studied may be inactive, active, or past, and are caused by either equipment or operational errors. FTA and bow-tie methods share their ground in exploration of preventive measures; however, the bow-tie method additionally observes mitigative actions. Therefore, both FTA and the bow-tie method can be used as a tool for risk assessments, but only the latter may be utilized for incident investigations as well (Manuele, 2020). However, usage of the bow-tie method may lead to obstacles with its difficulty to fully express complex workplace hazards and their probable sources and consequences (de Ruijter & Guldenmund, 2016).

Hazard & Operability Analysis

Hazard and operability (HAZOP) analysis takes a proactive approach and is generally applied during the design phase of a process (Ericson, 2015). The HAZOP model focuses on the probability of an incident and the consequences of the event. The HAZOP method demonstrates how process variations affect a system, where process demonstrations may result from events such as equipment failures and human errors.

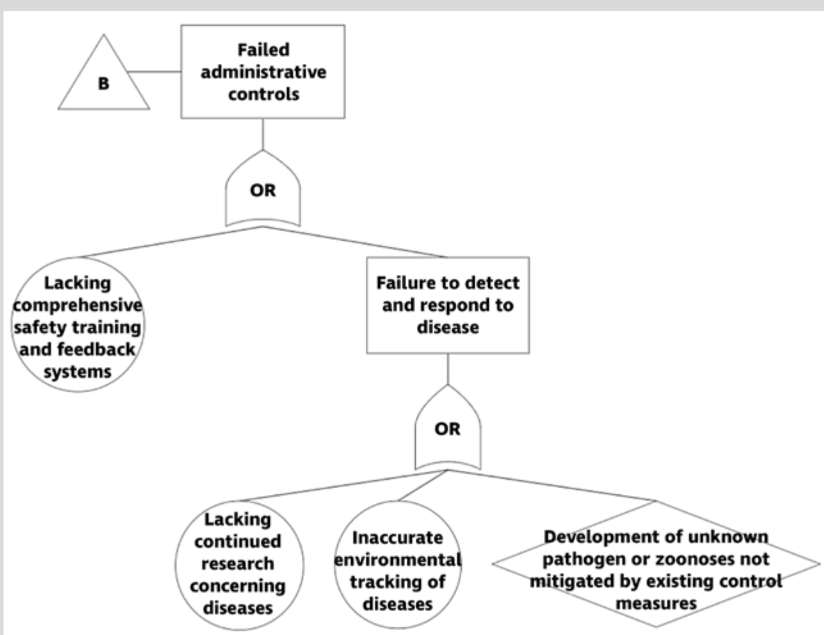
For HAZOP analysis, once a risk is identified, a multidisciplinary team can then brainstorm potential system hazards and use guide words to describe potential failures (Ericson, 2015). The HAZOP analysis team should note potential hazard consequences without employed safeguards and estimate (at best) the probability of the undesired event occurring. Once the severity and the hazard probability without safeguards are identified, a risk matrix can be consulted to better prioritize the need for controls. Here, risk is rated as either high, medium or low. The greater the risk, the more the employer should prioritize implementing or enforcing stricter controls. Next, the team of experts can recommend equipment design modifications, procedural changes or other hazard control measures. With these safeguards present, the risk may be reassessed to determine whether further alterations are necessary.

The benefit of this method is its ease of use and ability to help determine risk level. Because of its simplicity, HAZOP may not be as technical as other methods such as FTA, FMEA and bow-tie method. The main weakness of the HAZOP method is when utilizing the guide words and their deductive approach, there is a possibility of neglecting certain hazard causes if the sources do not relate to the noted guide words (Ericson, 2015). To ensure that all needed guide words are included, the process may require participation of additional safety experts with the company's initial safety team (Manuele, 2020). Given this, HAZOP analysis, like FTA, may be considered more

FIGURE 8

FTA FOR ZOOS: FAILED ADMINISTRATIVE CONTROLS, PART 3

Part 3 of the failed administrative controls intermediate event.



time consuming and expensive. But unlike FTA, the HAZOP technique may have a higher likelihood of missing potential hazard sources.

Method Selection

When evaluating these various methods for this application, FTA was selected because it provides a more in-depth analysis than other system safety techniques while still providing a visual depiction of the system. According to Manuele (2020), "The strength of an FTA is its ability to identify combinations of basic equipment and human failures that can lead to an accident" (p. 188). Unlike some other system safety methods, FTA accounts for human errors in addition to technical failures (Manuele, 2020). Another advantage of this method is its ability to involve both quantitative and qualitative data. It also successfully focuses on critical components related to the system failure and prioritizes mitigating the risk through corrective actions (Ericson, 2015). Finally, FTA is also useful for a reactive approach, measuring remedies after an event has already occurred (Ericson, 2015).

Unlike FTA, FMEA is a bottom-up approach that analyzes potential failures component by component rather than at a system level (Manuele, 2020). FMEA can recognize single failure points of a system more readily than other system safety techniques. As a result, this method is particularly useful in detecting failure modes in equipment. Yet, FMEA may not evaluate the system failures as extensively as FTA, and it is more suitable to "systems vulnerable to single failures that can lead to accidents" (Manuele, 2020, p. 188).

The bow-tie method is known for its simplistic visual design and applicability to both risk assessments and incident investigations (Manuele, 2020). However, there are limited uses for the bow-tie method (Voicu et al., 2018). First, it does not allow for a quantitative assessment of risk like FTA. Another downside of the bow-tie method is that each barrier is independent from one another. Additionally, in cases where hazard sources are linked in complex ways, this method may not be applicable.

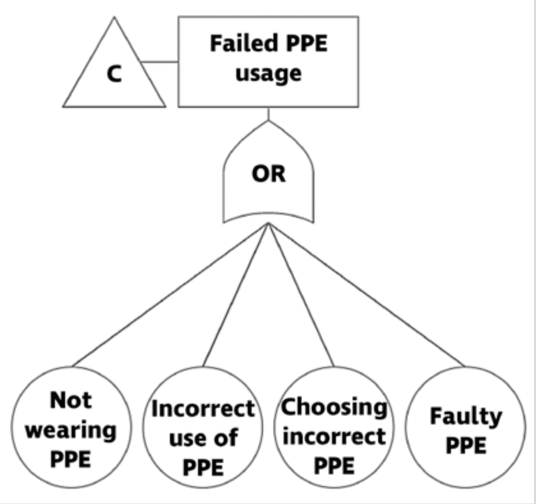
The HAZOP method is a highly structured, comprehensive tool that explicitly identifies hazards and evaluates the probability and severity of the event if the failure were to happen (Ericson, 2015). This method can also effectively include human errors as well as technical failures. The HAZOP analysis operates through a team of multidisciplinary experts who utilize brainstorming and guide words (Manuele, 2020). But, compared to FTA, like FMEA, the HAZOP model focuses on individual possible failure sources rather than a combination of possible failures that could lead to an undesired event (Ericson, 2015). Also distinct from FTA, HAZOP analysis lacks the ability to appropriately assess the effectiveness of existing hazard control measures as it is primarily used during program design phases.

FTA seems the most purposeful system safety technique for pathogen and zoonosis exposure hazard analysis in zoos because of a combination of its visual aid and simplicity, and its applicability to both risk assessments and incident investigations. If an employer is resistant to fund a more proactive approach by performing more hazard assessments and amending its safety program to support a safer work environment, displaying exactly how worker health and the business could be impacted may improve leadership's desire to engage. Demonstrating worker involvement opportunities in FTA may encourage employers to implement this method into their disease management safety program, too. Because FTA is a visual tool, including employees in initiating use of this method can further support professional development as well as protocol knowledge and compliance, continuing enhancement of safety and reliability in zoo facilities.

FIGURE 9

FTA FOR ZOOS: FAILED PPE

The failed PPE intermediate event.



FTA Application

The FTA model is recommended as the most appropriate method for this hazard. With the FTA model selected, the method may now be applied to management of the specific hazard of pathogen and zoonotic disease exposure in zoo workplaces; the FTA model for the hazard of pathogen and zoonosis exposure within zoo workplaces is presented in Figures 4 through 9. The top event equals a zoo worker falling ill due to an occupational exposure to a pathogen or zoonotic disease (Figure 4, p. 28). Intermediate events consist of failed engineering controls, failed administrative controls, and failed PPE usage following the hierarchy of controls (NIOSH, 2023). Due to the FTA's size, the intermediate events sections are depicted in Figures 5 through 9.

Figure 5 (p. 29) presents the failed engineering controls intermediate event. While less effective than hazard elimination, engineering controls materially separate workers from the hazard, and therefore reduce exposure risk via physical segregation. For instance, to better reduce zoo workers' direct contact with diseases such as *E. coli* infection from possibly ill animals, feasible engineering controls may include installing biosafety cabinets, ventilation systems, and footbaths, and designating physically restricted quarantine and isolation sectors.

Other engineering controls are sharps containers and storage areas for sanitized and sealed lab equipment for any chemical tests. In addition, zoo workers may use tools such as mops, brooms, and tongs or other grabbing instruments to maintain distance from potentially contaminated sources while cleaning or performing work tasks. By not implementing the necessary engineering controls, zoo workers may not be properly physically isolated from the hazard and consequently experience an increased risk of contracting diseases from zoo animals.

A portion of the failed administrative controls intermediate event is presented in Figure 6 (p. 29), along with its basic events. The rest of the administrative controls are depicted in Figures 7 and 8 (pp. 30-31). Although less effective than engineering controls, administrative controls prevent contact with the hazards through modification of and compliance with protocols. To better prevent zoo workers from contracting diseases such as *E. coli* infection through zoo animal contact, administrative controls such as disease reporting, compiling routine housekeeping and disinfection protocols, limiting access or time within high-risk zones, and ensuring staff compliance with these workplace protocols may be employed. Without these adequate administrative controls, zoo workers may experience increased risk of contracting diseases from the animals.

The failed PPE intermediate event is presented in Figure 9 along with its basic events. Despite PPE being less effective than administrative controls, PPE physically insulates workers from the hazard specifically through protective gear. Because it is the least effective measure in the hierarchy of controls, PPE should be used as a last-resort hazard control method. Wearing PPE may be beneficial in decreasing the likelihood of zoo workers contracting diseases such as *E. coli* infection through animal contact. To work effectively, PPE must be the correct type for the specific task and hazard, must be worn and used correctly, and must not be compromised. Without following proper PPE protocols, zoo workers have an increased risk of contracting diseases from animals.

If technical or human error led to a PPE failure in preventing contact with diseases, engineering and administrative controls are backup safety processes. If the administrative controls are also unsuccessful in preventing subsequent worker contact with pathogens or zoonoses, then engineering controls would still be present to aid in hazard exposure prevention. Nonetheless, even after application of the hierarchy of controls, if an engineering control fault occurred and the worker consequently experienced an exposure to the hazard, an incident may result. In this case, a work-related disease exposure and subsequent illness would be considered the loss. The technical or human errors that led to a faulty control measure are considered the active failed controls. While latent failed controls do not directly cause an exposure, these components should still be evaluated to minimize the likelihood of future incidents.

Discussion

Zoonotic diseases are considered a major public health concern with significant economic impact including direct and indirect costs (Gorji et al., 2022; Welburn et al., 2015). FTA-based hazard identification and risk management programs can reduce work-related illness cases and their costs by reducing hazard exposure probability and severity, reducing work-related illness cases and costs, and improving working conditions and safety culture. Moreover, accomplishing a stricter disease control and prevention program using the FTA method and incorporating the hierarchy of controls may help employees physically avoid illness cases and reduce linked emotional stress. As a result, workers may feel more protected and appreciated by their employer, leading to lower turnover rates and enhanced production (Manuele, 2020). Further, facilities can work together with other local, national, and international safety and health programs to strengthen relationships, create more precise FTAs, and more effectively reduce emerging infectious disease threats. The evaluated benefits of establishing FTA-based disease management programs in zoos may ultimately outweigh the analyzed costs, indicating that investment in these programs is worthwhile.

Recommendations

The FTA method can be recommended by zoo safety professionals as a novel tool to supplement existing biosafety principles and to continue recognizing possible causes for disease exposure among various zoo staff work tasks and successful safety program barriers against these hazards. With knowledge gained from this project, zoos and other environments can better understand direct and indirect costs as well as the probability and severity of potential health consequences from contact with biological hazards if adequate hazard control practices are not applied. Although many other potential hazards may be present in zoos, reducing chances of pathogen or zoonotic disease exposure can significantly reduce costs and positively impact the zoo field and allied professions. This evaluation is intended to highlight how the use of system safety techniques can fill gaps in routine risk assessments, amending and strengthening existing hazard communication programs, and implementing any additional necessary biological hazard control methods. OSH practice should continue to expand and improve through such studies, further ensuring worker safety and well-being.

Conclusions

Due to the high susceptibility of worker illness from exposure to pathogens and zoonotic diseases, hazard prevention and control measures are essential. The number of zoonoses is on the rise, and these diseases are spreading more rapidly due to habitat disturbance, transporting wildlife and other means. Zoo workers may lack knowledge about pathogens and zoonoses and awareness of their organization's safety plans. These individuals may not consistently comply with disease management protocols and may be at greater risk. Resulting work-related illnesses can create substantial loss for an employer from direct and indirect costs. To best protect zoo workers' safety and health, applying FTA in coordination with the hierarchy of controls and proposed hazard management practices may be considered.

This study compared four commonly used system safety analysis techniques to evaluate the hazard of disease exposure management in zoos, and the FTA method was ultimately selected for its visual aid, ability to both assess system failures and emphasize human errors, and its ability to detect necessary proactive and reactive hazard control measures. As pathogens and zoonoses evolve, zoo safety programs and other novel workplace environments could apply the FTA method to investigate potential gaps in their existing plans and use the conclusions to make improvements and better manage hazards. **PSJ**

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Emma C. Villarreal, M.S.O.S.M., ASP, ASHM, is a safety specialist at the University of Texas Medical Branch (UTMB) in the Life Safety and Environment of Care Compliance program. She was previously a research associate at UTMB, carrying out the role of a laboratory manager and Hazard Control Act trainer for a startup neurology lab in 2023. She also previously worked as a health scientist at CTEH LLC, where she provided toxicological litigation support and worked multiple projects involving emergency responses, industrial hygiene, and pandemic management. Villarreal holds an M.S. in Occupational Safety Management from Embry-Riddle Aeronautical University and a B.S. in Environmental Science from Baylor University.

Cheryl L. (Cheri) Marcham, Ph.D., CSP, CIH, CHMM, FAIHA, is an associate professor and program chair for the Master of Science in Occupational Safety Management program in the Worldwide Online Campus for Embry-Riddle Aeronautical University. She was previously the environmental health and safety officer for a major university for more than 26 years. She holds a Ph.D. and M.S. from the University of Oklahoma Health Sciences Center Department of Occupational and Environmental Health, and a B.S. in Biology from Arizona State University. Marcham is a professional member of ASSP's Oklahoma City Chapter.

Michael F. O'Toole, Ph.D., is professor emeritus of Aerospace and Occupational Safety and Adjunct faculty for the Master of Science in Occupational Safety Management program in the Worldwide Online Campus of Embry-Riddle Aeronautical University. He is also owner of O'Toole & Associates with clients in the U.S. and internationally. O'Toole holds a Ph.D. in Public Health Policy Administration from the University of Illinois Chicago, an M.A. in Industrial Psychology from Western Michigan University, an M.S. in Safety Engineering Technology from Northern Illinois University, and a B.A. in Behavioral Psychology. O'Toole is a professional member of ASSP's Northern Ohio Chapter.

Bart Eltz, Ph.D., CSP, CIH, is a corporate global EHS associate director for Duracell and has held positions with Fortune 50 companies such as Comcast NBCUniversal, Georgia-Pacific, CRH. He holds a Ph.D. in Emergency Management from Capella University, and a M.S. and B.S. in Occupational Safety and Health from Columbia Southern University. He started his career as an industrial hygienist for the U.S. Air Force, where he practiced industrial hygiene, environmental protection and radiation safety. Eltz is a professional member of ASSP's Georgia Chapter and a member of the Society's Industrial Hygiene Practice Specialty.