Incidents in Educational and Academic Chemistry Laboratories

A Comparative Case Study Project

by

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For this thesis, eleven published case studies of laboratory incidents that involved hazardous chemicals and occurred at primary educational and academic institutions were compared. The important information on the incident settings was used to construct bowtie diagrams. This visual method served as a helpful tool to find similarities and differences of the incidents. Common themes between the different cases were lack of supervision, lack of training, deviation from established procedures, and an inadequate or delayed emergency response. Failing barriers provided several pathways for the incidents to occur. Therefore, hierarchical risk management models could not adequately accommodate dynamic teaching environments. The results of this project show that primary educational and academic facilities need to make improvements to their risk management systems and work operations. Laboratory incidents continue to occur at a high frequency. Therefore, effective methods on how to teach chemical health and safety and how to communicate occupational risk need to be developed.

Incidents in Educational and Academic Chemistry Laboratories

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Master of Science in Occupational Safety

by

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Introduction

Many sources of hazards can be present in the workplace. Specifically, workers who are exposed to hazardous chemicals can experience serious acute and adverse health effects. It is a very difficult task to keep track of the intrinsic hazards that are associated with individual chemicals. More than 142 million substances can be found in the Chemical Abstract Registry. Safety Data Sheets are available for all those chemicals. All registered substances must be classified according to the Globally Harmonized System. There are nine hazard categories, corresponding to different physical and health hazards. Additionally, hundreds of hazard and precautionary statements are included in the Globally Harmonized System (Globally Harmonized System, Rev. 7).

In a typical laboratory setting, plenty of hazardous substances are used for a variety of procedures. A long-term study conducted by Center for Disease Control and Prevention (CDC) evaluated data of emergency room events involving hazardous chemicals from nine states. Between 1999 and 2008, 57,975 of those incidents occurred, of which, 4,621 resulted in 15,506 injured people. Most of the injured people worked in the chemical industry (1,753). Surprisingly, academia ranked second with 1,562 injuries (Hill, 2016). The U.S. Chemical Safety Board published a comprehensive list of incidents that involved hazardous chemicals and occurred in laboratories. They included data from January 2001 until July 2018 (APPENDIX). The information was received from multiple sources, including the news media and the U.S. Coast Guard's National Response Center. Not all incidents did undergo a secondary verification by the CSB and the agency does not exclude that additional laboratory may have occurred during the timespan for which the incident data was collected. The CSB list accounts for a total of 261 incidents; 49 occurred in laboratories of businesses and industries. These resulted in a total of 92 injuries and nine fatalities. The worst case had four fatalities and 14 injuries. For primary educational facilities (middle schools, high schools, and one exploration museum), 65 incidents took place which resulted in a total of 209 injuries and no fatalities. One high school had 17 injuries reported for a single instance. The greatest number of incidents was reported for colleges and universities. At those institutions, 147 incidents happened and resulted in a total of 197 injuries and one fatality. One person died at a university while 13 people were injured at a college in just one occurrence. The Chemical Safety Board conducted investigations for five incidents from the comprehensive list. Three of the investigations were done for educational facilities (a discovery museum, a high school, and a university), one for an industrial facility, and one for a church (Chemical Safety Board, 2018).

Incidents involving hazardous chemicals demonstrate the necessity that any laboratory should have an effective safety and risk management concept. Several different approaches for establishing a safe laboratory environment are possible. Administrative and engineering controls should be put in place; all people working inside the laboratory should receive adequate training and should be provided with access to safety-relevant information. Emergency drills, an emergency response plan, and a chemical hygiene plan are integral parts of a safe laboratory environment. Appropriate personal protective equipment (PPE) should be provided to everyone working inside the laboratory, as well as visitors. New procedures and protocols should be evaluated through a job hazard analysis (JHA). Procedures need to be constantly reviewed. The functionality of hazard controls and safety barriers needs to be assured. A safe laboratory environment cannot be based on fixed plans and controls. The risk management needs to involve over time and in accordance with the needs of the institute. Furthermore, it is important to note that knowledge about chemical hazards and risk perception play important roles when it comes to laboratory safety. All the people working in the laboratory should receive appropriate training and should frequently be evaluated on their safety knowledge and attitudes.

Even though there is sufficient knowledge about the risks of handling hazardous materials, institutions often just implement higher levels of control measures when laws and regulations require a change. Several barriers between the workers and the hazard would provide the best protection for human health. Still, the administration often relies on the solutions that seem to be the simplest and most cost-effective on first glance. The consequences can be devastating. The great number of examples for laboratory incidents for educational and academic institutions shows that tragic events occur with a high frequency. In some cases, the institutions improved their risk management systems because they experienced pressure from the public and the authorities. Sometimes real change was accomplished. Those improvements can serve as examples for laboratory management in general.

For this master's thesis, a comprehensive review of several case-studies that involved employees and students' exposure to hazardous materials in academic chemistry laboratories was be performed. Risk management systems and their surrounding safety cultures were evaluated. The goal was to identify flaws within those systems as well as cultural factors that influenced risk control measures from the outside. The purpose of this work was to identify common denominators of incidents that occurred inside the chemistry and research facilities of higher academic institutions and educational facilities.

Literature Review

Safety information and best laboratory practices are very important components of risk management programs in chemical laboratories. The literature review section of this paper will briefly elaborate on the recommendations, made by the American Chemical Society and researchers, on how undergraduate chemistry majors should be trained in regard to chemical safety. Next, a short overview of the Globally Harmonized System and selected chemical safety resources will be given. Then, the terms hazard and risk are going to be defined. A description of hazard controls and the bowtie method, a risk management technique, will be presented. The chapter will be concluded with information about comparative case study research and examples of what previous research was conducted around the issues with chemical safety in educational and academic laboratory settings.

Education for Professional Chemists

The American Chemical Society describes knowledge about chemical safety as a skill. It is not listed as a requirement of the undergraduate chemistry curriculum. The ACS guidelines state that approved programs should promote a safety culture. Students should understand safe laboratory practices and how to apply them. Safety awareness should already begin when students take their first introductory laboratory courses. Classroom and laboratory discussions must stress safe practices. Undergraduate students should learn about proper waste disposal techniques, comprehend and comply with safety standards, and understand and use material safety data sheets. They should be able to recognize potential chemical and physical hazards in the laboratory environment and know how to act in case of an emergency (American Chemical Society, 2018). Sigmann published a spiral diagram illustrating the learning evolution of a professional chemist (Figure 1). It depicts the educational journey of an individual as they progress from a high school student to a post-doc research chemist (Sigmann, 2018a).

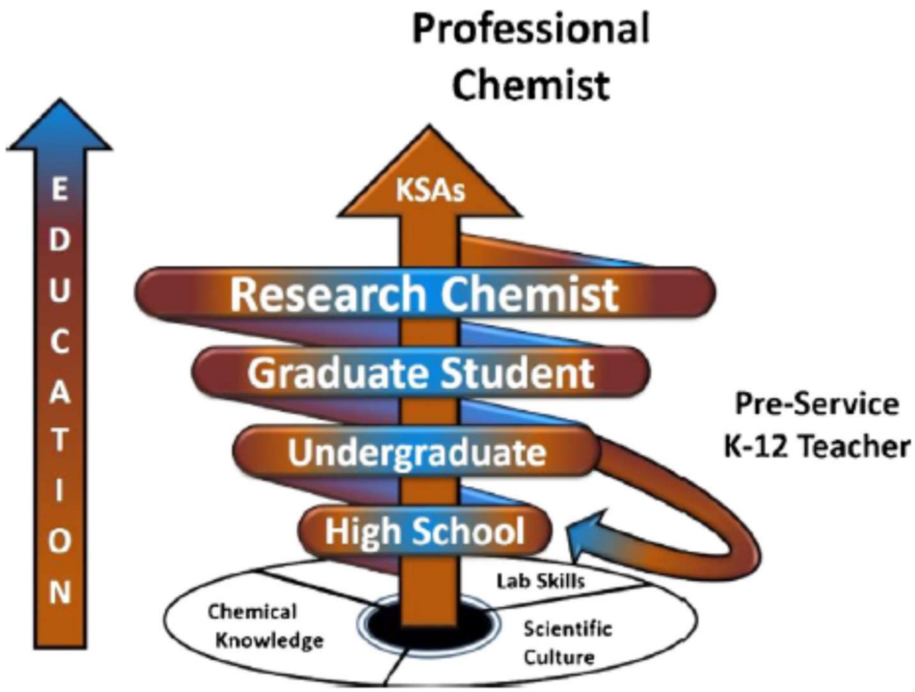

Figure 1. Learning evolution of a professional chemist (Sigmann, 2018a).

The central arrow represents the summary of knowledge, skills, and abilities a student needs to acquire in order to master the requirements for the profession of a chemist. Chemical knowledge, laboratory skills, and scientific culture have equal importance for the educational foundation of chemists (Sigmann, 2018a).

Safety resources. There is a variety of resources with chemical safety information available to chemists. The Board on Chemical Science and Technology published "Prudent Practices in the Laboratory: Handling and Management of Chemical Hazards" (National Research Council, 2011). Also, the Globally Harmonized System (GHS) was adopted for the United States in 2012. It includes a requirement for manufacturers and distributors of chemicals to provide their customers with safety data sheets (SDS) for their products. Therefore, the GHS is very helpful when it comes to the classification and verification of hazards for chemicals (Globally Harmonized System, Rev. 7).

Prudent Practices in the Laboratory. The National Research Council published a book that provides specific guidelines on how to implement prudent practices in a chemical laboratory. In the beginning, the authors provide a statement that laboratory workers realize the welfare and safety of individuals depends on clearly defined safety attitudes for the team but also for each worker. Safety cannot only be accomplished by using the right equipment and materials. It is influenced by processes and behaviors as well. The participation in the laboratory safety culture of habitual risk assessment, experiment planning, and emergency preparedness has the same importance as knowledge about the theoretical background of the experiments. Special safety considerations should be made for academic laboratories. They should be held accountable to the same safety standard as industry and research facilities, but the educators there also have the unique responsibility; students should be enabled to develop a lifelong attitude of safety consciousness, risk assessment, and prudent laboratory practices. Safety education should already start in primary school and should continue through postdoctoral training. Every student's first chemistry experiments in high school should cover a proper approach to understanding and dealing with the hazards that are associated with chemicals, e. g. flammability, reactivity, corrosivity, and toxicity. Another topic should be appropriate disposal of hazardous waste. When undergraduate chemistry courses are taught, the instructors face the challenge of introducing inexperienced students to the chemical laboratory safety culture. While some students might have already received good preparation from their chemistry high school course, others might have little to no experience in the laboratory setting. The learning goal is that all students can evaluate the wide range of hazards present in the laboratory and apply risk management techniques that are designed to eliminate potential dangers from the work setting. Undergraduate teaching assistants, who are often graduate students, should receive specific safety instructions from responsible faculty members. Teaching assistants serve as role models. Therefore, it is especially important to provide them with the tools and knowledge needed for the safe operation of the teaching laboratories. A written manual has proven itself as a very effective teaching tool for the laboratory assistants. It can include sections on the laboratory facilities, principles of laboratory safety, assignments during the laboratory sessions, management of chemicals, applicable safety rules and regulations, appropriate laboratory attire, PPE, departmental policies, emergency preparedness in the event of a fire, chemical spill, or injury. The entire faculty of the department should be fully committed to safe laboratory work practices. Safety should be a top priority for the educators as they create a foundation for the students later entering careers in industrial, governmental, governmental, and health science laboratories. If chemical safety is promoted during the undergraduate and graduate years of the students, the faculty and staff will have a significant impact on the future. For academic research laboratories, the engaged students must receive rigorous and mandatory safety training. Unlike teaching laboratories, where well-established experiments are repeated every semester, research often makes use of new materials and new methods. Those may pose new unknown hazards. Formal safety education for advanced students doing research should be made relevant to the actual work procedures. Principal investigators can be held legally accountable for the safety in their laboratories. However, this responsibility can be shared. Academic institutions often develop hierarchical structure so that the responsibility can be shared. A shared safety responsibility can help transmit the importance of prudent and safe practices. When everyone demonstrates leadership and a significant concern about safety, fewer people will get hurt in the laboratory. A partnership between the chemistry department and the environmental health and safety (EHS) personnel should be established. If a laboratory facility produces less waste, it will have smaller impact on the environment because a smaller quantity of waste needs to be disposed. A source reduction usually includes procedural and process alternations that use less material and produce less waste. Options should be discussed with educators and EHS managers (National Research Council, 2011).

Globally Harmonized System. The Globally Harmonized System (GHS) provides a uniform system for the hazard classification of chemicals and labeling of chemical containers. For the United States, the existing hazard communication standard (29 CFR 1910.1200) was changed in accordance with GHS in the year 2012. The committee that created the GHS worked for more than a decade and anticipated that with the implementation of the system, the protection of human and environmental health would be enhanced, a recognized international framework would be created, the need for testing and evaluation would be reduced, and international trade of chemicals whose hazards were properly assessed would be facilitated. The GHS includes harmonized criteria for the classification of substances according to their physical and health hazards and harmonized hazard communication elements for safety data sheets (SDSs) and labeling. In the GHS document, it is stated that an integral part of the system is the training of the hazard communication users. The key target audience for training includes employees, emergency responders, and risk management personnel. Containers of hazardous chemicals should always be labeled in accordance with the GHS. This also includes secondary containers in the workplace. Figure 2 shows the nine GHS Standard Pictograms (Globally Harmonized System Training by Multi-Clean., n.d.).

Figure 2. GHS Standard Pictograms (GHS Training by Multi-Clean., n.d.).

A GHS label also includes the signal words “Danger” or “Warning”. “Warning” is often used for the less server. Hazard and precautionary statements are a part of the label too. For the classification of health and environmental hazards, the following criteria were developed: (1) acute toxicity: (2) skin corrosion and irritation; (3) serious eye damage and irritation; (4) respiratory or skin sensitization; (5) germ cell mutagenicity; (6) carcinogenicity; (7) reproductive toxicity; (8) target organ systemic toxicity; (9) hazards to aquatic life. Physical hazards are classified according to the criteria: explosiveness, flammability, oxidizers, pyrophoric, organic peroxides, corrosives, gases under pressure, and water-active flammable gases (Silk, 2003).

Lists of unique codes for the statements can be found online and are intended for reference purposes (Globally Harmonized System, Rev. 7).

Safety Data Sheets (SDS). In 1968, the first Material Safety Data Sheet (MSDSs) communicating chemical hazard was published for the ship building industry (Kaplan, 1986). Since 1985, OSHA required chemical manufacturers and distributors to perform hazard evaluations and provide MSDSs for their products. OSHA required that the MSDSs contained information about: (1) name of manufacturer; (2) chemical and all common names of the hazardous components: (3) physical and chemical characteristics; (4) carcinogenicity potential; (5) first aid and emergency response; (6) primary routes of intake; (7) OSHA exposure limits and toxicity information; (8) physical hazards and reactivity: (9) health hazard data; (10) handling and spill clean-up; (11) engineering controls, recommended best practices, personal protective equipment (PPE); (12) preparation and dates for review of the MSDS (29 CFR 1910.1200, before 2012). OSHA did not require or provide a standardized format for MSDSs. Therefore, many manufacturers used the standard format that was developed by the American National Standards Institute (ANSI) in 1993 (American National Standards Institute, 1993). This ANSI standard contains all of the OSHA-required sections plus four additional sections; (1) toxicology information; (2) transportation; (3) safe disposal; and (4) ecological information. As the GHS System was adapted for the United States in 2012, MSDSs were renamed Safety Data Sheets (SDSs) (Globally Harmonized System, Rev. 7). The new SDSs have the following sections: (1) identification; (2) associated hazards;(3) composition; (4) first-aid; (5) fire-fighting measures; (6) accidental release measures; (7) storage and handling; (8) exposure control and personal protective equipment; 9) chemical and physical properties; (10) stability and reactivity; (11) toxicological data; (12) ecological information; (13) disposal considerations; (14) transport; (15)

regulations; and (16) further information. The GHS addresses in more detail what information should be included for those sections (Silk, 2003)

Under the Hazard Communication Standard, employers are required to provide information to their employees about the hazardous chemicals that are present at the workplace. They have to provide training, access to SDSs, and all containers have to be properly labeled. Since the manufacturers and distributors of chemicals are required to provide SDSs to their customers it is assured that the businesses who receive chemicals have an insight to the relevant and important information (Eastlake, Hodson, Geraci & Crawford, 2012).

Risk Assessment

A hazard may be an attribute of an activity, a circumstance, or a condition that is able to produce undesired events. Risk refers to a product of probability or likelihood for an undesired event to occur and the severity of the consequences for that event, as a result of a present hazard. Risk assessment includes strategic methods for the prevention of undesired events. Risk management addresses what to do about the risks that were identified during the risk assessment (Brauer, 2016). In 1983, the U.S. National academy of science published “Risk Assessment in the Federal Government: Managing the Process”. In this publication, the four steps of risk assessment for chemicals were described as: (1) hazard identification; (2) dose-response assessment; (3) exposure assessment; and (4) risk characterization (National Research Council, 1983). Risk assessment must often rely on inadequate information or the lack of data. Some people will take a conservative approach so that risk is not overestimated. Others will use comparison techniques for various options. The relative differences between options then become more important than absolute risk estimates for the individual approaches. The risk assessment criteria differ. For the United States, if there is no proof for a risk being present, people do not see a need for regulation. In Europe it is the opposite; if there is a chance for a risk, it is usually not allowed. The risk management process involves the following steps: (1) risk identification; (2) risk analysis; (3) elimination or reduction of risk; (4) financing risk; and administration of the risk management process. Adverse events can be caused by human error or system failures. Hazards can be controlled so that the likelihood of an undesired event is decreased. The hierarchy of controls is described in the literature (Brauer, 2016).

Concepts of error. Human error can be viewed in two different ways: the person approach and the systematic approach. The person approach assumes that errors are being made because of forgetfulness, inattention, poor motivation, carelessness, negligence, and recklessness. Blaming the individual seems to be emotionally more satisfying than targeting entire institutions. If an undesired incident occurs, attempts to uncouple a person's unsafe acts from any institutional responsibility are common. This is especially convenient for management. The person approach falls short because, without a culture of safety reporting, it is impossible to determine the causes of unwanted situations. Errors are often being made by the most skilled and most knowledgeable people. Recklessness and poor motivation can, therefore, be excluded. Unskilled workers do not have a monopoly on incidents. Undesired situations that seem random at first often have recurring patterns. Errors cannot be investigated without looking at the systematic context. Recordkeeping needs to include detailed analyses of all mishaps, incidents, and near misses. Trust is an integral part of a functioning safety reporting culture. As a consequence, the basis of it all is a just culture (Reason, 2000). In 1990, Reason distinguished between the two different types of human errors, failure of expertise and lack of expertise. Failure of expertise happens when a pre-established plan or solution is applied inappropriately. A lack of expertise is when a person is forced to do a task for which they were not able to establish a working routine yet. Figure 3 illustrates Reason’s Swiss cheese model of accident causation (Reason, 1990).

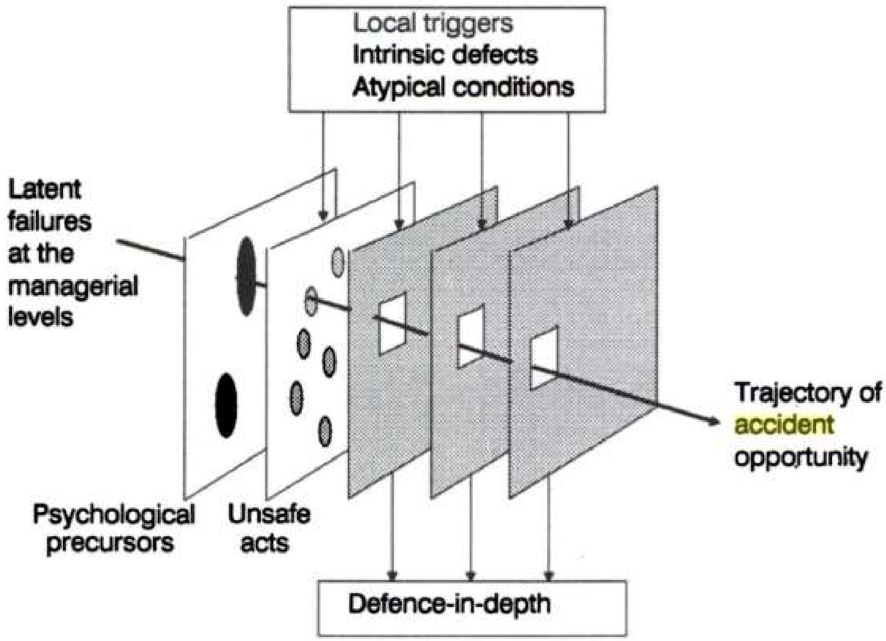

Figure 3. Swiss cheese model of accident causation (Reason, 1990).

The diagram shows a trajectory for an accident “opportunity” (Reason, 1990). Reason’s model describes the interactions between system-wide latent conditions, for example, poor safety designs and inadequate equipment, inadequate supervision or training, manufacturing defects, maintenance defects, and unsafe procedures. According to this model, each level of hazard control (defenses) has weaknesses created by the latent conditions or unsafe acts. This creates a “window of opportunity” for an undesired event to occur. An accident trajectory is able to breach the defenses and cause an incident (Reason, 1990).

Some researchers believe that most mistakes being made are due to management issues not due to lack of skills of the involved workers. Errors by workers can be attributed to poor management processes (Brauer, 2016). Deming published research for which he described that an existing process could not be improved from within unless there is a change made to the process itself. His approach was to focus on management monitoring the process correctly, reducing errors in poorly functioning tasks, and avoiding the necessity for corrections after errors occur (Deming, 1981). Figure 4 shows Rasmussen's risk management framework together with the migration of work practices. This illustration was published as part of the book "Human Factors Methods and Accident Analysis: Practical Guidance and Case Study Applications". The authors chose to combine concepts from Rasmussen's original publication in on picture (Rasmussen, 1997 as cited by Walker, Jenkins, Rafferty, Lenné, Stanton & Salmon, 2012).

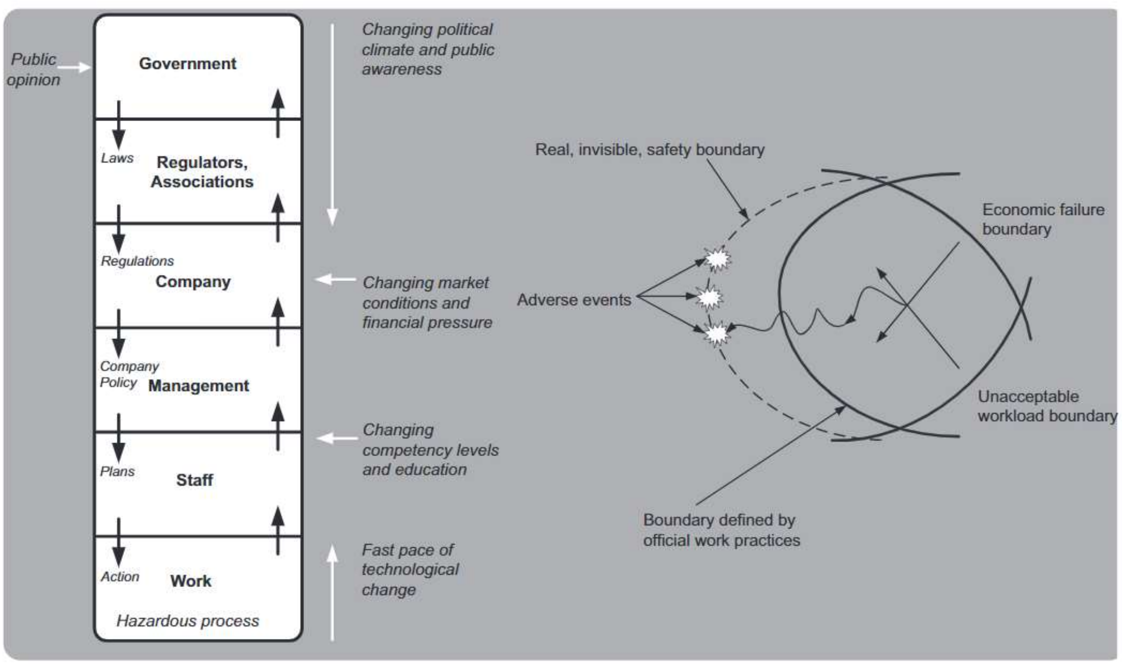

Figure 4. Risk management framework with the migration of work practices (Rasmussen, 1997 as cited by Walker et al., 2012).

Rasmussen explains that accidents are typically waiting to be released. The stage for this is set by the different people working within the system and participating in routine work practices. The model also describes how work practices evolve over time, and in doing so often cross safe work activity boundaries. Economics and productions influence work practices in a way that, after a while, leads to degradation of system barriers and migration of work practices. It is very important that the migration of safe work practices does not only occur at the system level where the work is performed but on all levels up to the top of the hierarchical structure (Rasmussen, 1997 as cited by Walker et al., 2012).

System failures. Changes in design can introduce new hazards to the system. This is especially true when a design change introduces a new hazard. During the design and planning phase, engineers and others may introduce new hazards for the sites of buildings, operations, and environments. A hazard can be the result of a computational error or making poor assumptions about how the system will operate (Brauer, 2016). Design errors of structures and equipment can lead to acute failures and latent failures for the system.

Hierarchy of hazard controls. Hierarchical control systems stress the view that those at the highest level of the hierarchy are in control. Those at the progressively lower levels have accorded levels of authority and control subordinates as instructed by the highest level of management (Lintern & Kugler, 2017). A good culture is an integral part of a functioning management system. If a new leader attempts to change the organizational structure of an institution, he would first have to erase elements of the old structure that hinder the improvement of the organization's culture. General management skills, as well as insider knowledge, are important qualities for personnel in leadership positions. Edgar Schein stated that nowadays a gap between practitioners and researchers is observable. There is an increased demand for applied knowledge and practical knowledge. Also, organizational cultures have become less important. The focus is now on a combination of occupational and national cultures. When tackling a business problem, it is important to tackle the cultural root cause first (Mike, 2014).

In order to protect workers' health and safety, an effective risk management system needs to be put in place. Risks that are associated with hazardous situations and materials need to be controlled. While a great variety of hazards can be present at different workplaces, the hierarchy of controls is a general approach to manage risks. Figure 5 shows the pyramid of the hierarchy of controls (CDC, 2018).

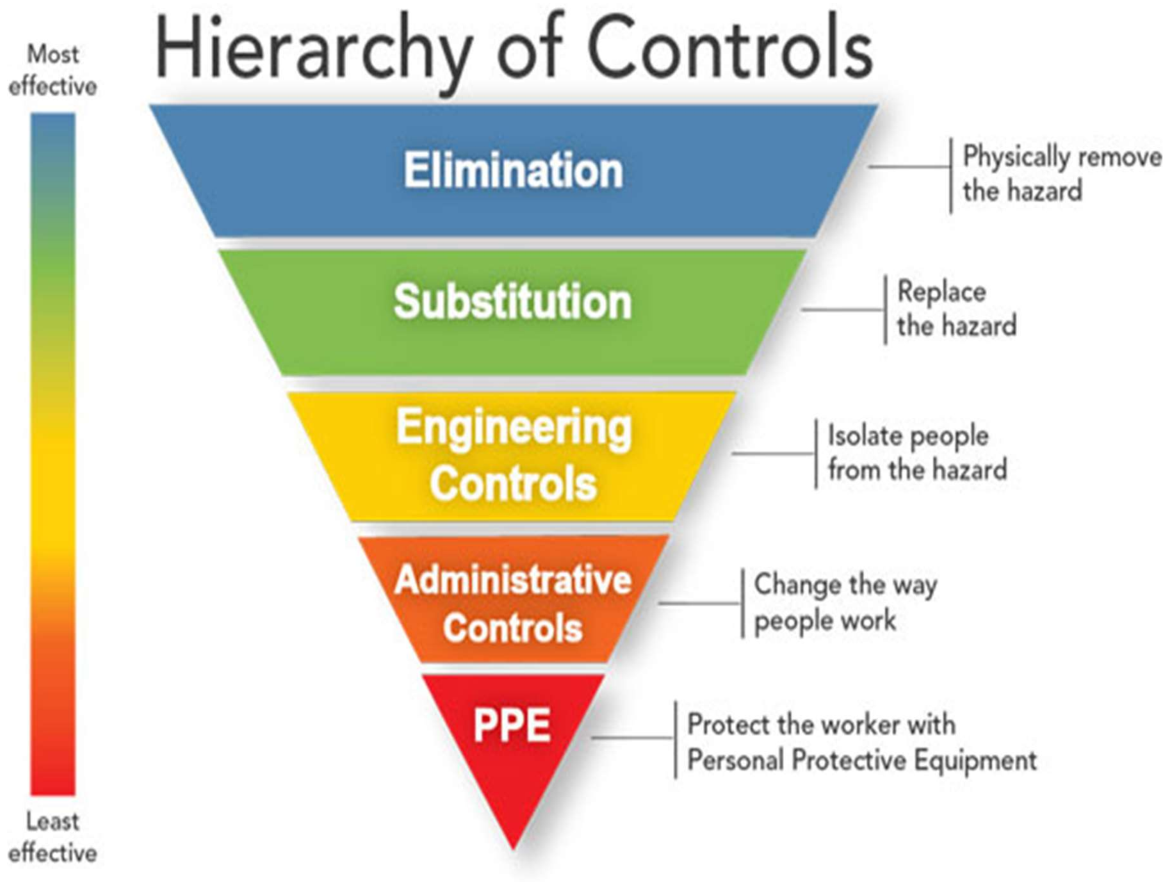

Figure 5. Hierarchy of Controls (Center for Disease Control, 2018).

Elimination is the most effective risk control; the hazard is physically removed. Substitution replaces the hazard with something else. While both controls are very effective, they are also very difficult to implement for already existing processes. If the process is still in development, elimination and substitution often can be realized easily and inexpensively.

If the higher levels of risk controls cannot be applied, engineering controls can be put in place. Those isolate the workers from the hazard. Well-designed engineering controls can be very effective in protecting workers and are typically independent from the actions of the workers. The initial cost of engineering controls can be high, but over time the costs of operation decrease and sometimes costs are even reduced.

The lowest levels in the hierarchy of controls are administrative controls and PPE. Both are used frequently for processes that are not very well controlled. They are inexpensive to establish but can be very costly to maintain over time. Both methods require significant effort by the affected workers and are known to be less effective than the higher levels of controls (CDC, 2018).

Risk Management Techniques

Several different risk management techniques are discussed in the safety literature. For this thesis, the bowtie methodology is described in detail below.

Bowtie methodology. The Bowtie Method is a risk management technique that can be utilized for the analyses and demonstration of causal relationships between hazards and their controls. The name of the technique originates from the shape of the diagram which resembles a bowtie. The model is said to have been presented for the first time as part of a chemistry lecture at the University of Queensland, Australia, in 1979 (The history of bowtie, n.d.). The bowtie is a graphical tool that demonstrates an incident scenario and the resulting outcomes. Bowtie diagrams can have different variations. Figure 6 shows a typical bowtie diagram (Dedianous & Fievez, 2006).

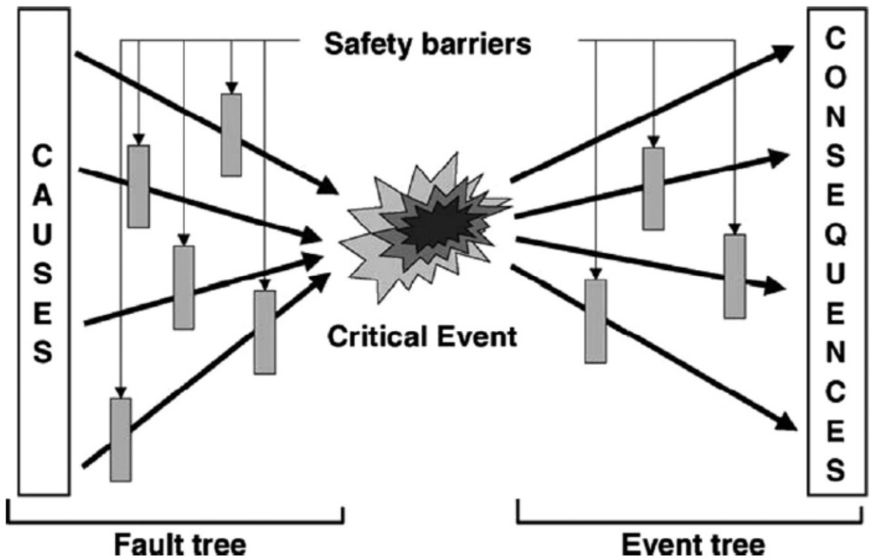

Figure 6. Bowtie diagram (Dedianous & Fievez, 2006).

In general, all bowties converge around an event for which control is lost. This event is often called the "top event" (Ruijter & Guldenmund, 2016), or "critical event" (Dedianous & Fievez, 2006). Threats and causes of the "critical event" are on the left side; they are elements of the fault tree. Consequences are on the right side; they are features of the "event tree". Barriers are fundamental elements of the bowtie diagram. They are placed on both sides of the "critical event". The goal for those barriers is to eliminate or inhibit the loss of control on the side of the "fault tree" and try to recover or mitigate the loss of control on the side of the "event tree". Additionally, a management system can be added to the bowtie diagram. The management system would serve as an additional layer underneath the barriers. It shows how a barrier is integrated and how it influences the other features of the bowtie diagram (Ruijter & Guldenmund, 2016).

Comparative Case Study Research

The UNICEF Office of Research presented an overview of comparative case study research in 2014. They explained the following: a case study is an extensive examination of a single case. This can be an incident, a policy, a program, and intervention site, or others. A comparative case study involves at least two case studies. It aims to produce more generalizable knowledge about causal questions. For example, why programs succeed and other programs fail. Comparative case study research is undertaken over time and emphasis's comparison with and across contexts. It can be selected when an experimental design is not feasible to undertake or when there is a need for an explanation on how features with the context influence a system. Comparative case study research includes the analysis and synthesis of similarities, differences, and patterns across two or more cases that share a common focus or goal. For a well-designed study, the specific features of each case should be described at the beginning of the study. The rationale for the selection of different cases is that all of them should be related to the key evaluation questions (KEQ) of the comparative case study. An understanding of each case is important for establishing the basis for the analytic framework. As a design option, comparative case studies are appropriate when "how" and "why" questions are posed on the outcomes of situations, when there is little or no opportunity to influence or control outcomes, and when an understanding of the context is seen as being important. The UNICEF Office of Research recommends a careful selection of cases is necessary because it has implications for how well causality can be addressed for the data synthesis and analysis process Figure 7 shows the research design (Goodrick, 2014).

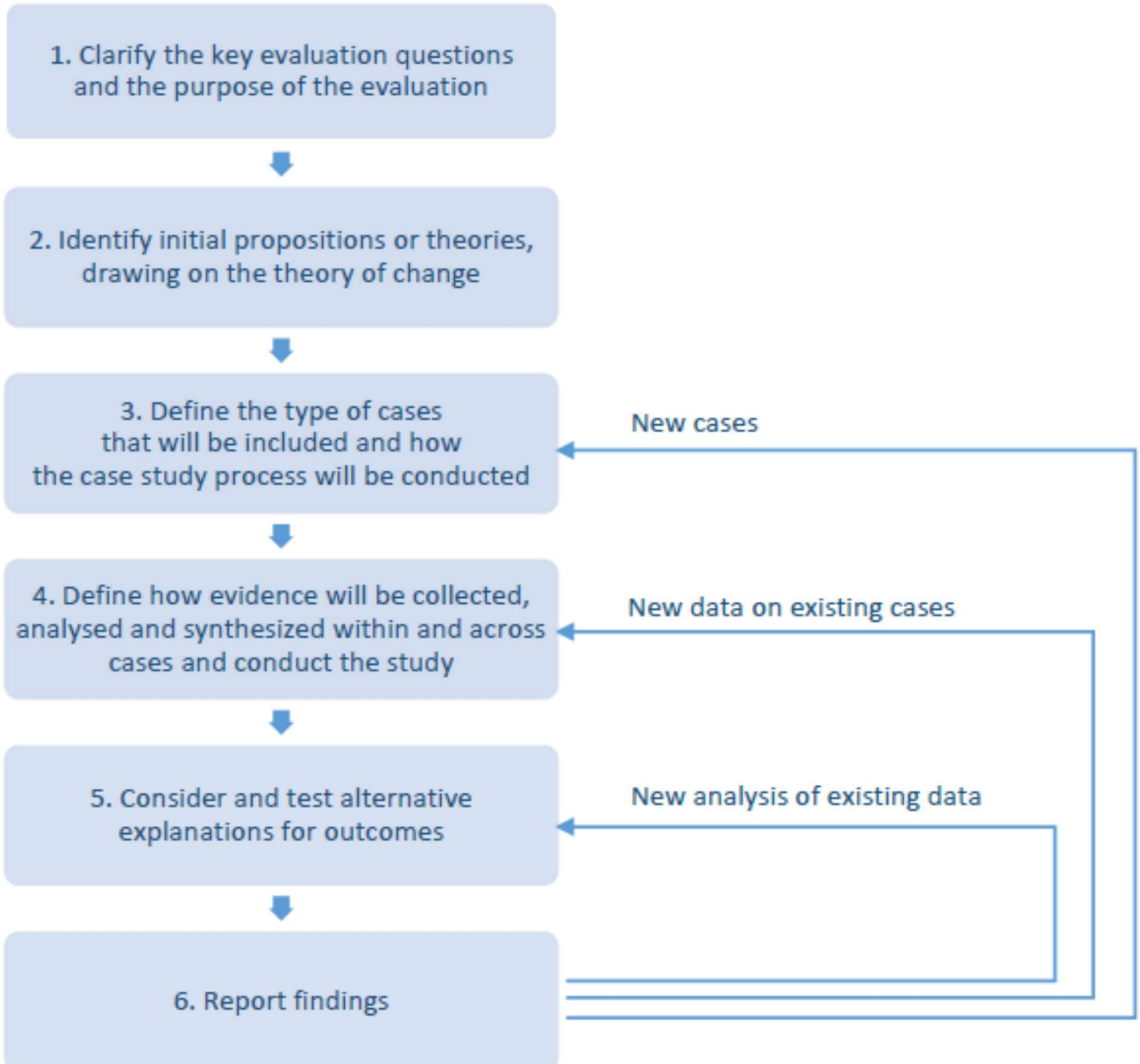

Figure 7. The logic of comparative case study research (Yin, 2014 as cited in Goodrick, 2014).

Comparative case study research usually involves six steps that, in an ideal situation should be undertaken in the following order:

1. Definition of the KEQ and the purpose of the study. This sets goals for the study and makes sure that a comparative case study research project is the appropriate design for

2. Identifying initial theories and objectives as a focus for the comparative case study.
3. Defining the selection criteria for case studies to be included in the project.
4. Identification of the methods for evidence collection, analysis, and synthesis across the different case studies.
5. Considerations of alternative explanations for the outcomes of the different cases.
6. Report on the findings and results of the comparative case study project.

This sequence provides the opportunity for selecting and testing explanatory evidence repeatedly, which is a major difference compared to experimental and quasi-experimental research designs (Goodrick, 2014). In 2017, an innovative approach in regard to comparative case study research was published by Bartlett and Vavrus. They portrayed the methodology as an innovative approach that attends simultaneously to macro, meso, and micro dimensions of case-based research. The comparative case study research promotes multi-sided fieldwork studies through and across sides and scales. They proposed that comparative case study research should attend to three axes: horizontal, vertical, and transversal comparison. The horizontal look should not only contrast cases with each other but also trace social actors, documents, and other influences across those cases. The vertical comparison examines influences at different hierarchical levels, from the international to the national to the regional and the local scales. The transversal is necessary for a comparison over time. In theory, the horizontal and vertical perspectives should be considered historically but often they are not. Therefore, the third transversal axis is needed (Bartlett & Vavrus, 2017).

Comparative case study research examples. Comparative case study research is conducted for a variety of disciplines. The following pages will describe selected cases studies the author of this thesis found relevant and applicable to the project.

Storage tank incidents. Chang and Lin compared 242 accidents involving storage tanks that contained hazardous chemicals in industrial facilities that happened over the last 40 years. The paper aimed to analyze the causes of those occurrences. The information about the 242 accidents was collected from public reports. They used the fishbone diagram (cause and effect diagram) that was invented by Dr. Kaoru Ishikawa for the identification of effects and causes that created the storage tank accidents (Ishikawa, 1985). The most accidents occurred for petroleum refineries (116), 64 cases happened at terminals and pumping stations, 31 cases at chemical plants, six cases on oil fields, and 25 cases at other industrial facilities such as power plants, gas, pipeline, fertilizer, and plating plants. The most frequent cause of loss was fire for 145 cases, explosions occurred for 61 cases. Oil spills ranked third (18 cases) and toxic gas releases fourth (13 cases). The distortion of tank bodies and worker's falling only occurred a few times. Lightning was the most frequent cause of incidents (80 cases), maintenance errors ranked second (32 cases). There were 29 cases of operational errors, 19 equipment failures, 18 acts of sabotage, 17 cracks/ruptures, 15 leaks and line ruptures, 12 cases caused by static electricity, eight open flame incidents, seven natural disasters, and five runaway reactions. Figure 8 shows the fishbone diagram for storage tank incident causes. Figure 9 displays the fishbone diagram of preventive measures for storage tank incident (Chang & Lin, 2006).

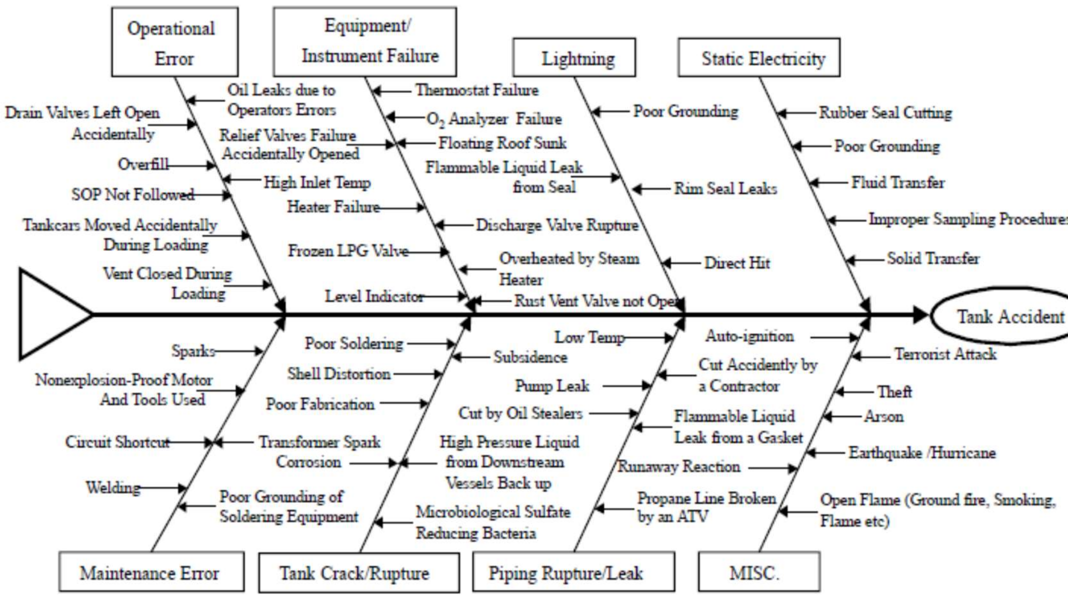

Figure 8. Storage tank incident causes (Chang & Lin, 2006).

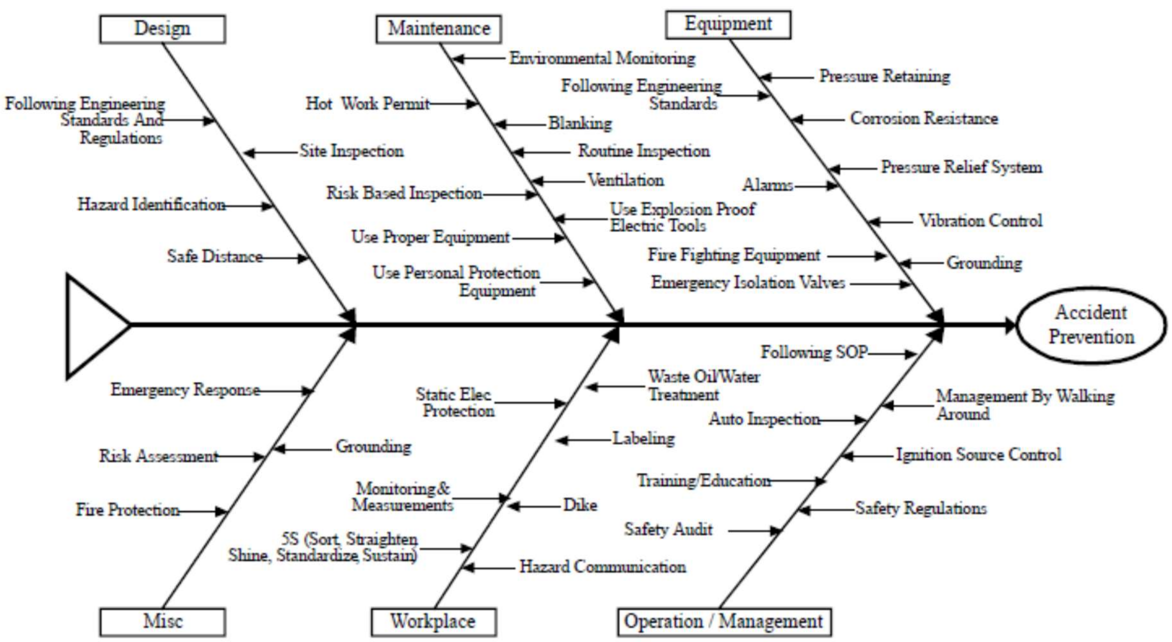

Figure 9. Preventive measures for storage tank incidents (Chang & Lin, 2006).

The researchers concluded that most of the storage tank accidents that had occurred could have been avoided if good engineering in design, construction, maintenance, and operations had been practiced and safety management programs had been implemented an executed (Chang & Lin, 2006).

MSDSs comparison and evaluation. In 2012, Eastlake et al. published about their comparison and evaluation of MSDSs for different nanomaterials. A sample of 59 MSDSs was collected from 2007 to 2008 from 32 different manufacturers. In 2010 to 2011, 21 additional MSDSs were obtained. Additionally, 23 MSDSs from the first set of 2007 to 2008 were recollected for comparison in order to determine if improvements and revisions had occurred. The MSDSs were evaluated based on questions intended to determine if the content was informative and safety-relevant. It was of special interest if hazard identification, exposure controls, appropriate PPE, and toxicological information were included. A statistical analysis was performed. For the 2007 to 2008 set, 21.8 percent were satisfactory, 40.6 percent needed improvement, and 37.5 percent needed significant improvement. The most common deficit was the lack of toxicological data specific to the nanomaterial and the particle size range was not included. For 59.4 percent of the MSDSs occupational exposure limits (OEL) for the bulk material were listed but no OEL for the nanomaterial was mentioned. The recollected MSDSs were compared to the originals which showed that an overall decrease in the percent of MSDSs ranked satisfactory or in need of improvement and an increase in the number of MSDSs ranked in need of significant improvement. For the set of 2010 to 2011, the most common deficiency was a failure to specify that the material is in the nanometer size range. As a conclusion, this study revealed that important information was not being developed or included on MSDSs for nanomaterials. They recommended extensive literature reviews on the specific nanomaterials. The obtained information can then help with the improvement of the MSDS (Eastlake et al., 2012).

Research Exploring the Chemical Safety Culture for Academia and Educational Facilities

Recent publications focus on the topic of chemical safety climate and safety culture at academic institutions. Among those articles are evaluations of conducted surveys, recommendations for establishing safety programs at academic institutions, effective teaching methods for safe practices in the chemical laboratory, and concepts how to provide chemists with the necessary knowledge, skills, and experiences during their undergraduate studies.

Epidemiology of accidents in academic laboratories. Hellmann, Savage, and Keefe conducted an accident intervention study based on the results of a statewide chemistry accident survey that was conducted in Colorado, and additional observations that were made about academic chemical laboratory accidents as a whole. Two institutions were selected from the institutions that participated in the statewide survey. The data of their accident rates were adjusted for accidents per 9,000 student hours for each semester from spring 1974 to the fall of 1983. During the intervention semester the chemistry professors of Institution A who were teaching general, organic, and quantitative analysis received a summary for the statewide survey database to supplement their safety instruction for the fall semester of 1984. Additionally, a new accident report form was provided. This new form was considered important for establishing legal responsibilities. During the intervention semester, the accident rate for institution A increased from 0.24 accidents per 9,000 students to 0.47 accidents per 9,000 students. For the control institution, Institution B, the accident rate decreased from 1.13 accidents per 9,000 students to 0.36 accidents per 9,000 students. The researchers concluded that the increased accident rate for Institution A could be due to a change of behavior because the students knew that they were being observed. Additional explanations were underreporting that had taken place at Institution A for the previous three semesters and that classroom lectures about safety that were given to at-risk student populations were not the most effective way of accident prevention and control. The detailed analysis of the data indicated that three environmental factors can contribute to the risk of generating accidents in an academic chemistry laboratory: the design of equipment and facility, the activity or function required for the laboratory exercise, and the available PPE. Each of those components can be altered or improved so that a decrease of the frequency for laboratory accidents can be archived. The practicality of their potential to reduce accidents depends on the purchase and maintenance costs, the degree of reliance on human behavior, and the ease of adaptability to new circumstances. The researchers concluded that the most effective way of reducing incidents at academic institutions is the improvement of design and building features so that the risk and safety management system does not have to rely heavily on appropriate student conduct in the laboratory facilities (Hellman, Savage & Keefe, 1986).

Safety climate at public universities. In 2016, researchers published a study for which the evaluated the safety climate at a Louisiana State University by utilizing data from a previously conducted survey. The institution had suffered from a natural disaster in 2008 when hurricane Gustav made landfall. A survey of laboratory personnel was conducted in 2011. This was done by graduate students who did a project for their environmental science course. Approximately 150 people were asked to participate and about 85 responded. The initial survey data, which was intended to estimate the impact of a hurricane on research facilities and to prepare for future events, was culled to 26 questions related to laboratory safety concerns. The goal was to estimate the safety climate levels in the laboratories and to assign a numerical value. The questions were divided into three groups that corresponded to already existing safety climate studies performed at other academic institutions. The safety perception was determined by the answers to the questions that concerned potential hazards, hazardous events, emergency response, security, and feeling unsafe. The commitment of direct supervision to safety was determined by questions about PPE use, enforcement of PPE use, training, audits, use of standard operation procedures (SOPs), access to MSDSs, and housekeeping. The upper management's commitment to safety was evaluated by asking about safety equipment, practices that support safety, such as chemical inventory, fire drills, and fire extinguisher inspections. Figure 10 shows the percentage of laboratory personnel by length of service and position. Table 1 displays questions related to the upper management commitment to safety and the corresponding results. Table 2 illustrates questions related to the direct supervision commitment to safety and the corresponding results. Table 3 shows questions related to workers' safety perception (Steward, Wilson & Wang, 2016).

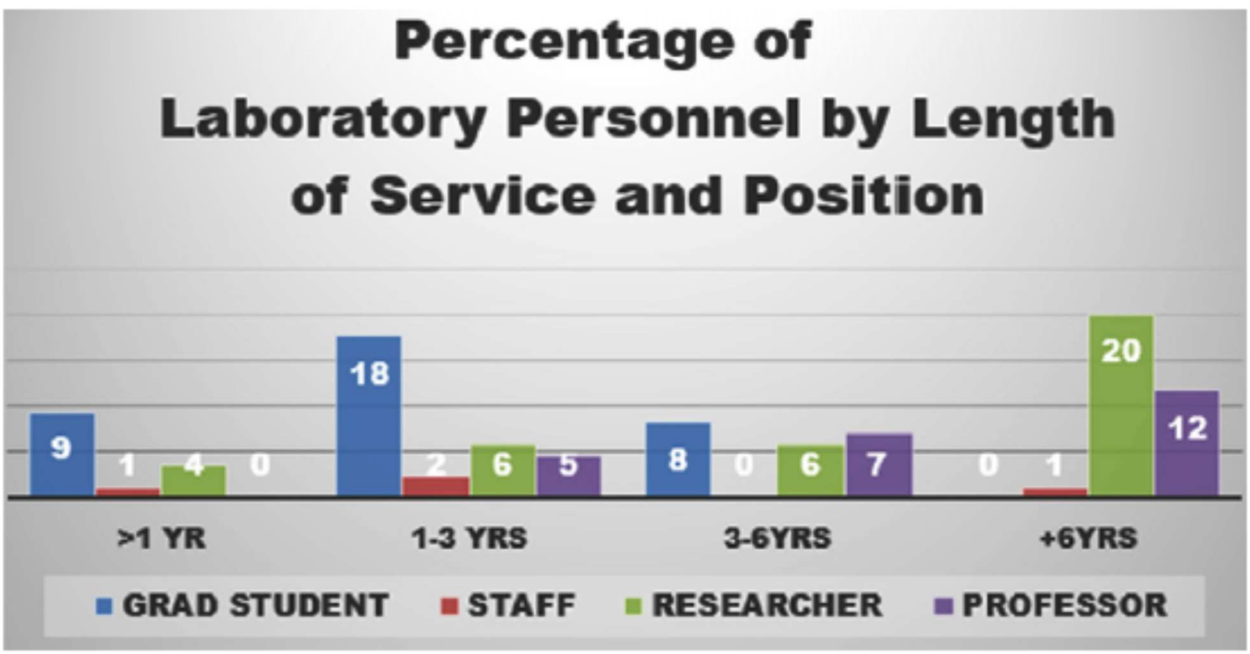

Figure 10. Percentage of laboratory personnel by length of service and position (Steward, Wilson & Wang, 2016).

Table 1. Upper management commitment (Steward, Wilson & Wang, 2016).

Analysis Group	Number	Question	Analysis Label	*N*	Mean	Std Dev	Cronbach Alpha	Eigen Value
PHY	Q.9	Are fire drills performed?	DRILL	85	3.56	1.76	0.28	1.57
PHY	Q.11	Does the lab have functioning emergency showers?	SHOWER	85	3.63	1.81	0.32	1.39
PHY	Q.12	Does the lab have emergency eye wash stations?	EYE	85	4.13	1.62	0.12	1.13
PHY	Q.13	Does the lab have hood vents?	HOOD	85	4.72	1.03	0.31	1.06
PHY	Q.16	Are there fire detectors & fire suppression equipment in the lab?	F_DETECT	85	4.01	1.53	0.19	0.91
PHY	Q.17	Are the fire extinguishers regularly inspected?	EXTIN	85	4.11	1.22	0.25	0.80
PHY	Q.20	Are chemicals inventoried?	CHEM	85	4.48	1.20	0.35	0.41
PHY	Summary	Total components		595	3.99	1.57	0.29	–
PHY	Summary	Principle components		340	4.01	1.64	–	–

Table 2. Direct supervision commitment (Steward, Wilson & Wang, 2016).

Analysis Group	Number	Question	Analysis Label	*N*	Mean	Std Dev	Cronbach Alpha	Eigen Value
DEPT	Q.14.1	Is PPE required to work in lab?	PPE	85	4.74	0.97	0.49	2.32
DEPT	Q.14.1	Is the PPE requirement strictly enforced?	ENFORCE	85	3.94	1.65	0.41	1.32
DEPT	Q.18	Has the lab staff been trained on the proper use of extinguishers?	EX_TRAIN	85	3.31	1.73	0.46	1.10
DEPT	Q.22	Are there general safety inspections?	GEN	85	3.52	1.55	0.42	1.09
DEPT	Q.23	How would you rate the labs overall housekeeping measures?	HK	85	1.92	1.36	0.58	1.03
DEPT	Q.30	Are there written standard operating procedures (SOPs)?	SOP	85	4.27	1.30	0.43	0.77
DEPT	Q.30.1	Are there written emergency SOPs?	WRITTEN	85	3.44	1.61	0.41	0.74
DEPT	Q.33	Are these emergency procedures easily accessible?	ACCESS	85	3.94	1.14	0.44	0.64
DEPT	Q.34	Are material safety data sheets (MSDS) available on demand?	MSDS	85	4.79	0.82	0.50	0.54
DEPT	Q.6	Were you required to complete a safety training course prior to working in the lab?	TRAIN	85	2.85	1.97	0.49	0.45
DEPT	Summary	Total components		850	3.67	1.66	0.49	–
DEPT	Summary	Principle components		425	3.48	1.74	–	–

Table 3. Worker's safety perception (Steward, Wilson & Wang, 2016).

Analysis Group	Number	Question	Analysis Label	N	Mean	Std Dev	Cronbach Alpha	Eigen Value
PREC	Q.15	Does the lab have potential for fires or explosions?	FIRE	85	2.69	1.91	0.016	1.86
PREC	Q.24	During your employment, have any hazardous events have occurred which jeopardized the lab or its staff?	EVENTS	85	4.36	1.45	−0.03	1.10
PREC	Q.26	Have you ever felt unsafe in your lab due to a hazardous event?	FEEL	85	4.15	1.17	0.15	1.03
PREC	Q.27	How would you rate your lab's response to potential hazards in the past?	RATE	85	3.91	0.78	0.23	0.97
PREC	Q.28	How well do you feel/think your lab was for prepared for the hurricane?	HURR	85	3.62	1.03	0.21	0.82
PREC	Q.42	What is the general security of the lab?	SECUR	85	2.11	0.66	0.11	0.69
PREC	Q.44	Are you aware of the potential for adjoining areas that would pose a significant risk during a lab emergency?	RISK	85	2.86	1.534	0.14	0.5613
PREC	Summary	Total components		595	3.51	1.45	0.15	–
PREC	Summary	Principle components		255	3.74	1.71	–	–

An ANOVA was completed for each question in order to determine if there was a significant difference between rank and time of service on each question. The questions were grouped according to the categories PHY (physical safety equipment), DEPT (department; represents the safety commitment of direct supervision), and PERC (perception of safety). The ANOVA results were only significant for "length of service" and "number of accidents". Participants with over six years of experience had a significant increase in hazardous events. Additionally, a factor analysis was performed. Only questions with Eigenvalues greater than one were significant for the estimation of the safety climate at the university. Assuming an equal weight for those questions, the values for the perceived safety climate were 3.72 ± 1.71 (on a scale from 1, "low", to 5, "high"). The survey showed that the perceived safety climate was in the same range as for previously conducted surveys for five other universities. The significant numerical factors used in the determination of the managerial level of safety commitment (PHY) at the University were related to providing physical safety items for the laboratory like fire suppression, laboratory hoods, and safety showers. Nearly all of the participants responded that

PPE is required in their laboratory work areas, but enforcement and training for use of PPE did not seem satisfactory. The survey showed that inspections were conducted, but the types of inspections were not specified. In general, laboratory personnel felt that housekeeping in the laboratory is a problem. As many employees indicated that they knew about the existence of SOP's in the laboratory, but the survey did not address details about the format of those and if the employees knew where to find them. About half of the participants indicated that they did not receive a form of mandatory safety training before they started working in the laboratory. The researchers concluded that assigning numerical values to different parameters for a safety climate was a difficult task and those metrics were hard to define and difficult to collect. The question of the relative merit of a safety culture at universities was left open for debate. Behavioral and situational aspects have not been fully considered for the academic environment. Methods to address safety concerns need to be developed and validated (Steward, Wilson & Wang, 2016).

Construction of bowtie diagram for the Texas Tech laboratory incident. In 2016, the Division of Chemical Health and Safety (DCHAS) conducted an interactive symposium at an American Chemical Society Conference. The group exercise for the participants of the symposium was to create a bowtie diagram for an incident that involved hazardous chemicals. The facilitators used the example of the 2011 CSB case study of a laboratory incident that occurred at Texas Tech University in Lubbock, Texas (Mulcahy, Boylan, Sigmann & Stuart, 2017). At the chemistry department, a graduate student was severely injured while handling a highly energetic metal compound that suddenly detonated (Chemical Safety Board, 2010). The people at the symposium were asked to identify the hazard, the top event, the threats and consequences, as well as preventive and mitigative safety barriers. The group quickly identified the energetic material has the "hazard", and the exceeding of the safety critical limit as the "top event”. However, they made the typical initial mistake of listing failing barriers (no written SOPs; no PPE: untrained workers; lack of communication; and no supervision) as threads. The actual threads were intentional and inadvertent synthesis scale-up and the criminal activities of the graduate students. The consequences were defined as injury/fatality, reputation damage, and loss of funding. The final result of the symposium is depicted in Figure 11. Some examples of preventive barriers were restricted access to the laboratory, pre-approval of procedures, and strict synthesis limits for new materials. Mitigative barriers were PPE, activate alarm and emergency response, communications with the primary investigator, and others (Mulcahy et al., 2017).

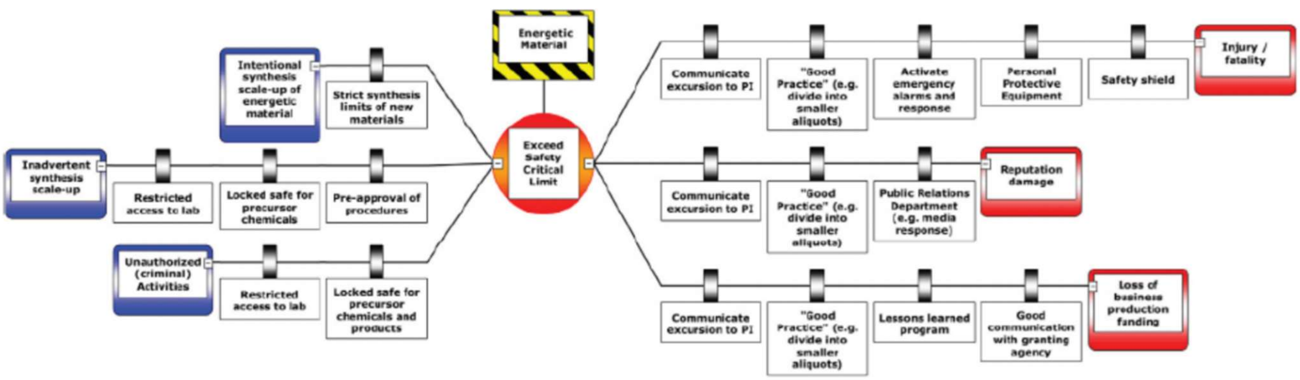

Figure 11. Completed bowtie for Texas Tech laboratory incident (Mulcahy et al., 2017).

The danger of chemistry demonstrations. Sigmann recently published an article that explained some of the serious issues of chemistry demonstrations. Over the past 20 years, almost 200 children and educators were injured because they participated in chemical demonstrations that involved the use of fire and flammable solvents. The “rainbow demonstration” has proven itself as especially problematic. For the demonstration, a row of dishes, each containing a different salt and methanol is used. Methanol is filled into the dishes and the mixtures are ignited. The goal is to produce a color scheme that has the colors of a rainbow. In order to characterize and assess the hazards associated with the experiment, Sigmann constructed a bowtie diagram (Figure 12) for the setting of flammable solvent demonstrations (Sigmann, 2018b).

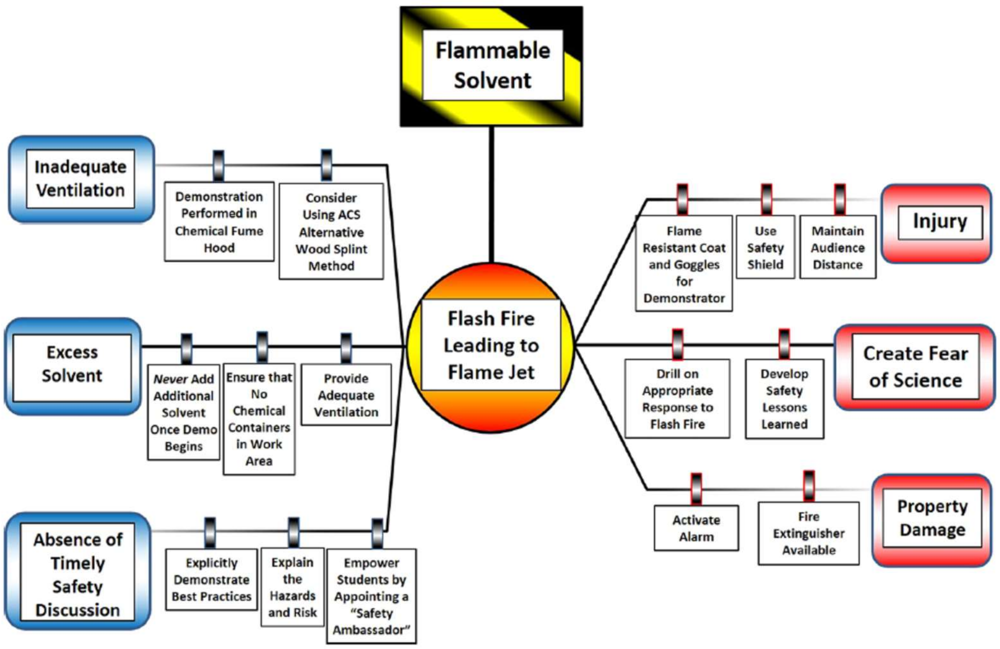

Figure 12. Bowtie diagram for flammable solvent demonstration (Sigmann, 2018b).

The hazard present because of the flammable solvent. The critical event is a flash fire leading to a flame jet. Threads that can lead to the critical event are inadequate ventilation, excess solvent, and not conducting a timely safety discussion. The consequences of the critical event could be injury, property damage, and creating a fear of science. Preventive barriers can be engineering controls, such as adequate ventilation and chemical fume hoods, and administrative controls such as training and procedures. Examples for mitigative barriers are an active alarm system and fire extinguishers.

It is Sigmann's conclusion that the safety problems with chemical demonstrations are continuing because to "blow stuff up" is a great fascination for many, especially children. Educators are competing against filmmakers and bloggers. The demonstrations have to be most spectacular. Many written procedures have been published, yet they often lack complete risk assessment of the hazards for the demonstrations. Propagation to educators about negative consequences might help to prevent some of the incidents in the future. Advocating for change and holding educators accountable to a standard duty of care is necessary to accomplish change. Additionally, K-12 teachers need to be educated about the safe handling of chemicals. A variety of electronic resources is available, and this information should be utilized before demonstrations begin (Sigmann, 2018b).

Methodology

Purpose of Study

This study intended to compare published case studies of laboratory incidents that involved hazardous chemicals and occurred in the United States. The project was intended to provide insight on the laboratory work settings of educational and academic institutions. In order to understand the dynamics of those work systems, it was important to dissect all the available information about the hazardous incidents and to put it in context to the general work setting. In order to do an objective comparison, the publications that described the hazardous incidents needed to provide detailed information about the settings of the cases. It was the goal to identify different components of the hazardous incidents and then construct bowtie diagrams with the obtained information, using computer software (BowTieXP, 2019). The bowtie methodology helps not only to evaluate the effectiveness of the preventive and mitigative barriers that were put in place but also to make recommendations about what important risk management components were missing. The identification and evaluation of common flaws for the selected cases can potentially help with the improvement of risk management frameworks of other locations as well. The communication and education of chemical health and safety is an important component for the occupational health and safety program at primary educational facilities and academic institutions. One limitation of this study was that the evaluation of the different laboratory incidents was based on information that was included to the publications and incident investigations. This project had to rely on the accuracy and completeness of the provided details. The author was the only person analyzing the case studies and constructing the bowtie diagrams. In order to eliminate potential bias, it was a goal to exclude personal opinions and only to utilize the published information.

Selection of Case Studies

For most cases that were included to the list published by the U.S. Chemical Safety Board, just basic information about location, date, and time of the incidents, involved persons, and results had been published. Detailed information was not made available to the public. Only two cases from the list which occurred at academic or educational institutions had in fact been investigated by the U. S. Chemical Safety Board. For this thesis, those two hazardous events together with nine additional case studies about laboratory incidents were analyzed. All of them occurred at different academic and educational institutions located in the United States and were either published in peer-reviewed academic journals or incident investigations. The recommendations for conducting a comparative case study research project that were published by the UNICEF Research Office were followed (Goodrick, 2014):

Selection of the Key Evaluation Questions. Since the project aimed to find common denominators between the different cases and flaws for the associated risk management systems it was very important to define the different components of those systems. The protagonists, the hazard which led to the critical event, the threats, the consequences, the preventive and mitigative safety barriers including their functionality were outlined. Furthermore, it was also of interest if there is any information about safety improvements that were made after the critical events occurred.

Initial theories. The initial theories can be derived from evidence presented in the news are that academic and educational institutions often do not have functioning chemical health and safety management and control systems. Hazardous incidents occur with a high frequency. Personnel and students do not receive adequate training or do not have sufficient knowledge before the start of conducting potentially dangerous experiments that involve the use of hazardous chemicals. Regulations and laws need to be adjusted so that universities, colleges, and primary academic institutions are held to a higher standard of accountability.

Criteria for the selection of the case studies. The criteria for selection were (1) case studies were published in peer-reviewed academic journals or published investigations by the Chemical Safety Board; (2) incident occurred in a primary educational institution or academic institution; and (3) the case study included detailed descriptions of the setting, measures of risk management, and consequences of the incident. Table 4 gives an overview of the case studies the author was able to collect.

Table 4. Overview of the selected case studies.

Case	Title	Institution Type	Author or Source, Year
1	CXXV. An Accident with Acetic Acid and Bromine	University	Burnett, 1975
2	Hazards in a Photography Lab - A Cyanide Incident Case Study	University	Houk & Hart, 1987
3	Injury and Fire Resulting from Benzene Vapor Explosion in a Chemistry Laboratory	University	University of California, Irvine Independent Accident Investigation, 2002
4	Mercury Spill Decontamination Incident at the Rockefeller University	University	Santoro, 2006
5	Texas Tech University - Laboratory Explosion	University	Chemical Safety Board, 2010
6	Laboratory emergency response: A case study of the response to a 32P contamination incident	University	Ashbrook, 2011
7	Case study -Incident investigation: Laboratory explosion	University	Phifer, 2014
8	Key Lessons for Preventing Incidents from Flammable Chemicals in Educational Demonstrations	Educational Museum	Chemical Safety Board, 2014
9	Report to the University of Hawaii at Manoa on the Hydrogen/Oxygen Explosion of March 16, 2016	University	Merlic, Ngai, Schroeder & Smith, 2016
10	Case study - A two-liter pyridine spill in an undergraduate laboratory	University	Eichler, 2016
11	Case study: Reaction scale-up leads to incident involving bromine and acetone	University	Chance, 2016

Evidence collection. The author used the publications to identify the parameters that answer the Key Evaluation Questions. With those results, bowtie diagrams for each case study are going to be constructed. This visual method will hopefully help with find common denominators for each case. The results are going to be synthesized and discussed.

Results and Discussion

In the results chapter, the different case studies are summarized. The protagonists, the hazard, the critical event, the threats, the consequences, as well as the preventive and mitigative safety barrier, are identified and illustrated as components of bowtie diagrams. Information about safety improvements for the institutions where the incidents occurred is included in the case summary when it was part of the publication. Bowtie diagrams are constructed using the software BowTieXP (BowTieXP, 2019) and have been embedded between each case description and discussion. The discussion of the findings that resulted from the evaluation of the different laboratory incidents includes answers for the key evaluation questions that were defined in the methodology chapter. The special interest is focused on similarities and differences for the cases. Two of the cases, Case 5:" Texas Tech University – Laboratory Explosion" and Case 8:" Key Lessons for Preventing Incidents from Flammable Chemicals in Educational Demonstrations", incident assessments were previously performed and published (Mulcahy et al., 2017, and Sigmann, 2018b). The results of this comparative case study are therefore compared to the previously published results. This illustrates the advantage of the comparative case study research objective; it is possible to repeatedly test evidence without repeating the incident or experiment (Goodrick, 2014).

Case 1: CXXV. An Accident with Acetic Acid and Bromine

A graduate student assistant received the task of preparing two liters of a solution that contained 0.05 M bromine and 90 percent acetic acid (glacial acetic acid). The author of the publication assumes that the student was not able to find glacial acetic acid and therefore attempted to make it from acetic acid anhydride. He attempted to prepare two solutions. No other students were present in the laboratory at the time. For Solution A, he added 900 mL acetic acid anhydride to 100 mL of water and then added 0.8 grams of bromine. He worked inside a fume hood. The bottle was gently shaken and transported from Laboratory 1 to Laboratory 2 which took about 5 to 10 minutes. Then he prepared Solution B the same way as solution A, except this bottle was vigorously bubbling and left in the fume hood of Laboratory 1. The student left Laboratory 1 for another task and as he came back, he found Solution B bubbling violently. He placed himself off-center and attempted to remove the plastic cap from the bottle of Solution B. This was when it exploded. The student received two deep cuts on one arm. He left the room and was seeking help at the nearby chemical stockroom and research laboratories. While first-aid was administered, Solution A exploded in Laboratory 2. The second explosion took place within minutes of the first. The author describes that, after the incident, the safety policies and regulations of the department were updated. He also suggests that graduate students should receive safety training as part of their orientation (Burnett, 1975).

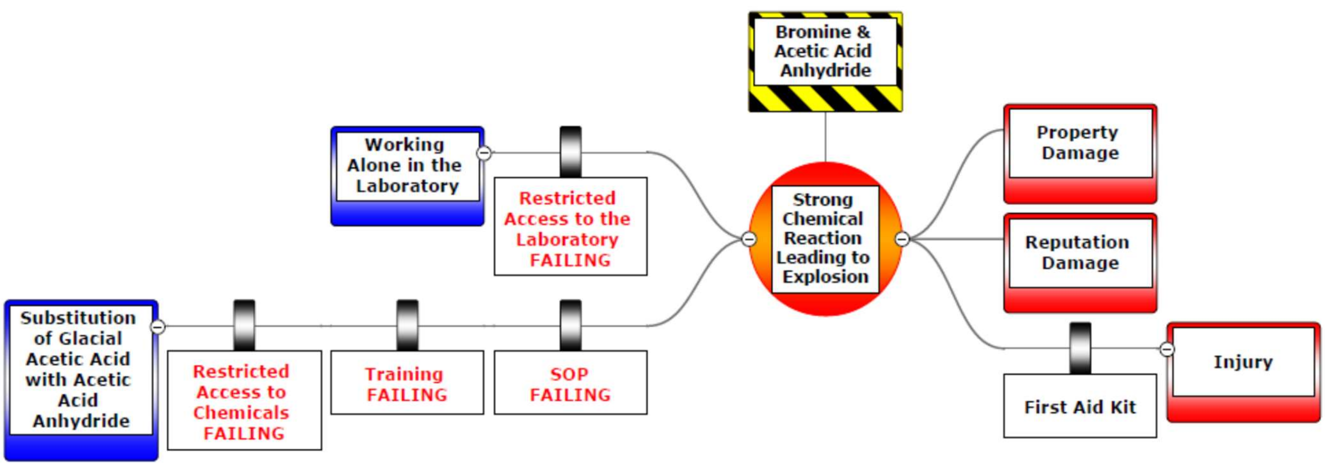

Figure 13. Bowtie of acetic acid anhydride/ bromine incident.

Discussion. The bowtie diagram shows that the institution had several failing preventive barriers. The graduate student assistant should have received adequate safety training before he started to work in the laboratory. This usually includes reading the safety data sheets of the chemicals that are used for the preparation of mixtures. He should not have had unrestricted access to the chemical stockroom and the chemical inventory. Also, while he had found the solution vigorously bubbling, he should not have tried to remove the cap from the flask. He should have had a written SOP procedure available that specifically described how to make the bromine/acetic acid mixture. This university seemed to have a lack of supervision. Also, graduate students did not receive safety training as part of their orientation.

Case 2: Hazards in a Photography Lab - A Cyanide Incident Case Study

The author mentions two incidents that involved that resulted in the release of hydrogen cyanide at a photo laboratory. Just the second incident is described in detail. Therefore, it is the only one used for this comparative case study research project: As part of their lecture, a faculty member demonstrated a cyanotype process technique to several students at a darkroom. For developing the pictures, he used a 50/50 mixture of potassium ferricyanide (cyano A) and ferric ammonium citrate (cyano B). Both mixtures contained 5-10 percent of the active ingredient. The faculty member was aware that hydrogen cyanide could be released because a similar incident had occurred at a previous workplace. Four photos were coated using the mixture. The sink was flushed with large volumes of water. The faculty stated that the workplace was found clean and dry before he started processing the pictures. After the first photo was processed, dried, and exposed to UV light outside of the darkroom, the group went back inside and found the remaining pictures still dripping and wet from the applied mixture. The faculty member noticed the characteristic almond smell of hydrogen cyanide and the students simultaneously started complaining about headaches. The group evacuated the area and notified housekeeping, environmental health and safety personnel, as well as the local fire department. The building was evacuated completely and fire personnel, equipped with self-containing breath apparatuses sealed the exits. The building was occupied the following morning. An investigation failed to establish an exact cause for the incident. Bad housekeeping was suspected. An acid of some sort most have been on the countertops below the wet pictures. The mixture was dripping on the surface and as a result, hydrogen cyanide was released. It was also determined that the ventilation of the darkroom was turned off during the incident. The faculty member did not even know that a ventilation system was installed in the room. The reason behind it was because the ventilation system was not properly functioning and made loud noises when it was turned on. At the end of the publication, the author included a list of safety precautions for the handling of cyanide-containing materials and advises faculty members and photo lab managers to strictly enforces the safety regulations (Houk & Hart, 1987).

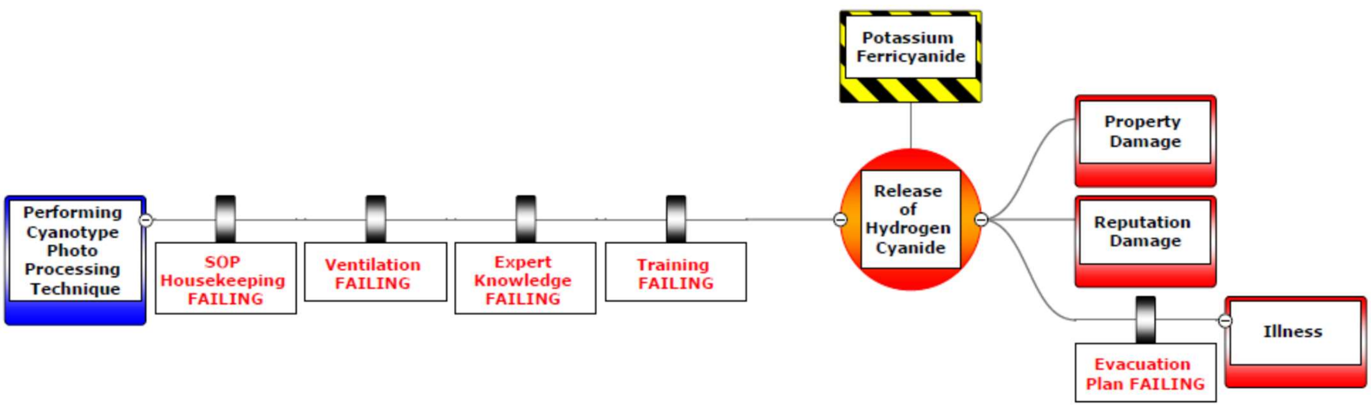

Figure 14. Bowtie of cyanide incident.

Discussion. The university did not have any written procedures for how to conduct housekeeping in the darkroom. The ventilation of the darkroom was not properly functioning and turned off because it made loud noises. The faculty member did not even know that the ventilation system existed. On the other hand, he was aware of the possibility that hydrogen cyanide could be released during the developing procedure of the pictures. Still, he did not apply his knowledge and brought it to the attention of the department so that the work process could be changed. It was not possible to determine the cause of the incident. Only after housekeeping, environmental health and safety personnel, and the local fire department were already notified, the building was evacuated completely. This case shows that the institution did not only have server communication issues, but also no functioning risk management program that could have assessed the situation in the teaching facilities and aimed to improve the situation.

Case 3: Injury and Fire Resulting from Benzene Vapor Explosion in a Chemistry Laboratory

The publication describes an accident that occurred on July 23, 2001, at the University of California, Irvine, located in Irvine, CA. The accident occurred in a chemistry laboratory and resulted in an injury to a graduate student and a fire that caused approximately $3.5 million in damage. The student was also a University employee working for a principal investigator's funded project. He received serious burns from a benzene vapor explosion that occurred inside of a laboratory fume hood. The student was purifying benzene using a reflux/distillation apparatus. Eventually, the system became over-pressurized and the student tried to physically hold the distillation head on the flask. The over-pressured system disassembled at the sintered glass fitting between the two glass components. A fine mist of benzene was released into the fume hood. This was where an unknown source ignited the benzene vapor which resulting in an explosion and subsequent fire. The direct cause of the over-pressurization was not determined. However, it was assessed that the lack of a clear path from the distillation flask through the pressure-relief portion of the apparatus resulted in the system disassembling and releasing the benzene mist of benzene. The student, who was standing in front of the fume hood, was burned by the fire and explosion. He received first- and second-degree burns on the face, neck, right arm, and right leg received first- and second-degree burns. The student was wearing safety glasses when the incident occurred. He evacuated the room and was taken by private automobile to the UCI Medical Center, where he was hospitalized for four days. The student did not suffer from any long-term health effects caused by the accident, and he graduated on time with a Ph.D. in chemistry. His professor and fellow students, who were present while the incident occurred, evacuated the laboratories on the second floor. The resulting fire activated a smoke detector tied into the building fire alarm system. After a couple of minutes, two manual fire alarm stations were also pulled. Emergency response to the scene was immediate and the resulting fire was extinguished within two hours. Except for the laboratory where the incident had occurred and the adjacent instrument room, the entire building was reoccupied within five days (University of California, Irvine Independent Accident Investigation, 2002).

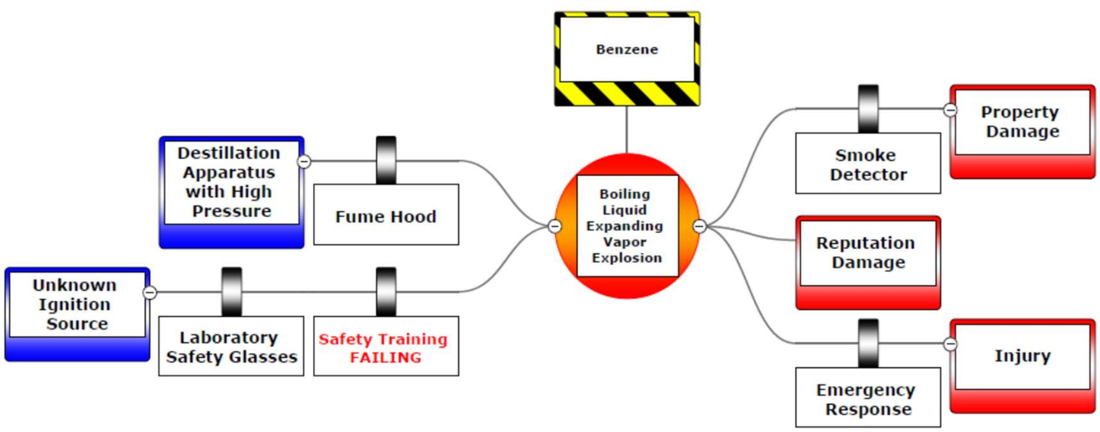

Figure 15. Bowtie of benzene vapor explosion incident.

Discussion. UC Irvine had several functioning controls and barriers in place. The student was working inside of a fume hood and the student was wearing safety glasses during the time the explosion occurred. A smoke detector was activated by the fire and two fire alarm stations were pulled. This initiated a timely emergency response so that the building was reoccupied within five days. The failing preventive barrier in this case was training. If the student had had adequate training, he would not have attempted to physically hold the distillation head of the apparatus in place. After the incident occurred, he was taken to the hospital by a private automobile. There was no information included in the publication whether it was against protocol to use a private vehicle for the transport of injured individuals.

Case 4: Mercury Spill Decontamination Incident at the Rockefeller University

A mercury contamination incident that occurred in August of 2003 at the Rockefeller University in New York City, New York. Approximately two grams of mercury supposedly evaporated completely. The substance can be absorbed into the human body by inhalation of its vapor and through the skin. Acute inhalation exposure to mercury vapor can result in chest pains, dyspnea, coughing, hemoptysis, and occasionally interstitial pneumonitis leading to death. The central nervous system is the target organ for mercury vapor exposure (PubChem, 2019). The amount originated from a mercury thermometer that was left unattended in a hot water bath. The incident occurred in a cold room with an average temperature of 1 °C. The room contained many biological samples that belonged to different research groups, as well as expensive laboratory equipment, stock chemicals, radioactive materials, radioactive and biological waste. The extensive decontamination of the room was finished after three weeks. Several thousand dollars were spent on the salaries of clean up personnel, analytical sampling of the room, and the waste disposal of the debris that contained mercury. Many laboratory samples and materials were lost. The author encourages researchers to take advantage of the mercury thermometer exchange program that is offered by the Rockefeller University. Thermometers that contain alcohol or spirit are offered at no charge (Santoro, 2006).

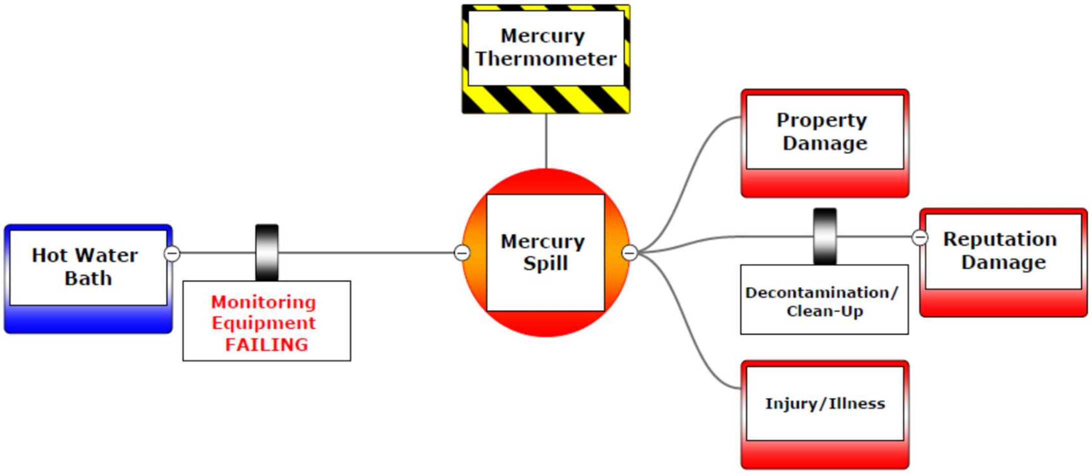

Figure 16. Bowtie of mercury spill incident.

Discussion. A mercury thermometer was used to measure the temperature of a hot water bath that was left unattended. The author stated that many samples were lost, and the decontamination & clean-up was very costly. It would have been easy to replace the mercury thermometer with an alcohol thermometer or a digital model. It is also very problematic that a large number of samples and reagents were stored in the work area. It is best practice to keep chemicals and reagents in a designated stockroom and samples that need to be stored long-term in a designated storage area. Just samples that are currently processed and reagents that are currently in use should be in the working areas of the laboratory. Furthermore, it is unclear why a hot water bath was left unattended in a room that had the temperature set to 1°C. This case shows that Rockefeller University did not only have deficits for planning and conducting their laboratory procedures but also for the design and organization of work areas and storage spaces.

Case 5: Texas Tech University – Laboratory Explosion

The U.S. Chemical Safety Board thoroughly investigated a laboratory explosion that occurred at Texas Tech University in Lubbock, Texas (Chemical Safety Board, 2010). This case previously served as an example to construct a bow-tie diagram at an ACS conference (Mulcahy et al., 2017). The situation was described as follows: About a month before the incident, a fifth-year graduate student together with the first-year graduate began with the synthesis of a nickel hydrazine perchlorate (NHP) derivative. The synthesized amounts of the compound were between 50-300 milligrams. The students ran several analytical tests in order to determine the quality and purity of their product. They determined that they would need several batches of the compound to complete all necessary analyses. Therefore, they decided to scale-up the synthesis of NHP and make about 10 grams of the product. The principal investigators were not consulted on the decision to scale up the synthesis. No written policies about any laboratory procedures existed at the time. The two students had previously discovered that smaller amounts of the compound would not ignite or explode on impact when wet with water or solvent. They concluded that the hazards of greater amounts of NHP could be controlled similarly.

After the scale-up, the more senior student noticed clumps in the synthesis product.

He transferred about half of the synthesized NHP into a mortar, added hexane, and then used a pestle to break up the clumps. It had not been evaluated if the use of either water or hexane was suitable for the mitigation of the potential explosive hazards associated with the quantity of the synthesized product. First, the more senior graduate student was wearing goggles, but he removed them as he walked away from the mortar after he finished breaking the clumps.

As he returned to the mortar, he did not replace his goggles while he stirred the product once more. This was when the compound detonated. After the incident, all the universities who were partners in the ALERT program executed a voluntary stop-work order in the laboratories for working with energetic materials. This was maintained until safety changes were implemented and independent reviewers could audit the laboratories' written safety procedures and standard operating procedures (Chemical Safety Board, 2010).

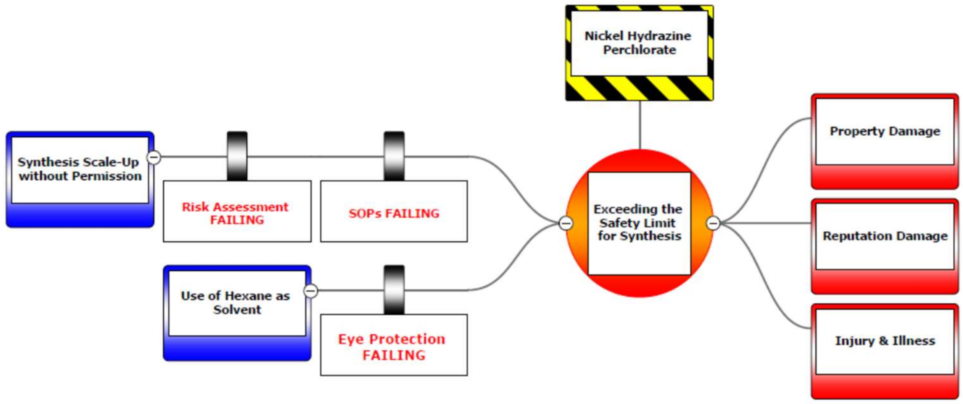

Figure 17. Bowtie of Texas Tech laboratory incident.

Discussion. The two graduate students that were involved in the incident decided to scale-up the synthesis without consulting their principal investigator first. Another publication already described this as criminal behavior (Mulcahy et al., 2017). The information that was described in the report of the U.S. Chemical Safety Boards did not provide enough detail to evaluate the intentions of the students. However, it can be assumed that they did not have sufficient knowledge about the hazards of the mixture. Together with their principal investigator and the chemical hygiene officer of the department, they should have conducted a risk assessment before they made any changes to the protocol of the synthesis. The more senior graduate student also made the mistake of removing his eye protection while he was conducting the experiment. In any laboratory where hazardous chemicals are present, proper eye protection should be required at all times. It is important to communicate to students, that they should make it a habit to wear proper eye protection, even when it seems inconvenient. It was a very good practice that the university communicated the occurrence of the hazardous incident to other universities and a voluntary stop for procedures that involved energetic materials was executed until the investigation of the incident was concluded. This potentially prevented similar incidents at other academic institutions. The information about the hazardous incident needs to include detailed information about the setting, the involved people, how the incident progressed, and the results.

Case 6: Laboratory emergency response: A case study of the response to a 32P contamination incident

A contamination incident with radioactive material occurred on a Monday afternoon at the University of Missouri in Columbia, Missouri. EHS personnel was contacted by a radiation worker who informed them that he had accidentally contaminated the soles of his shoes with radioactive phosphorous isotope 32P and was asking for advice. The health physicist who answered the call determined that there were enough uncertainties with the information that a response was necessary. When he reached the laboratory, the health physicist confirmed some contamination in the laboratory. He further questioned the laboratory worker and became suspicious that contamination may have been spread beyond what was first stated. A second health physician and the other two safety professionals realized that they would need additional assistance. They contacted the Radiation Safety Officer (RSO), who was off campus on that day and not able to personally respond. Therefore, he informed the EHS director. The EHS director dispatched an assistant director and called additional staff members to the site. Most of them worked through the night and tried to determine the extent of the contamination and tried to keep it from spreading further. Access to the contaminated areas was restricted, custodial and maintenance services were suspended. By Tuesday morning, contamination was found in the building where the source laboratory was located, in two additional buildings, and in multiple locations on outside sidewalks. The clean-up continued and by Thursday, the Principal Investigator reviewed his inventory and stated that the spill could only consist of 10 microcuries of 32P or less. The emergency response activities continued throughout the week. As a result, the number of restricted areas, as well as the size of the contaminated areas decreased each day until only the source laboratory was an area of concern. When the operation was completed, EHS had spent 500 man-hours for the response. The cleanup costs, excluding man-hours, were assessed at $40,000. The main costs resulted from the removal and replacement of flooring materials (Ashbrook, 2011).

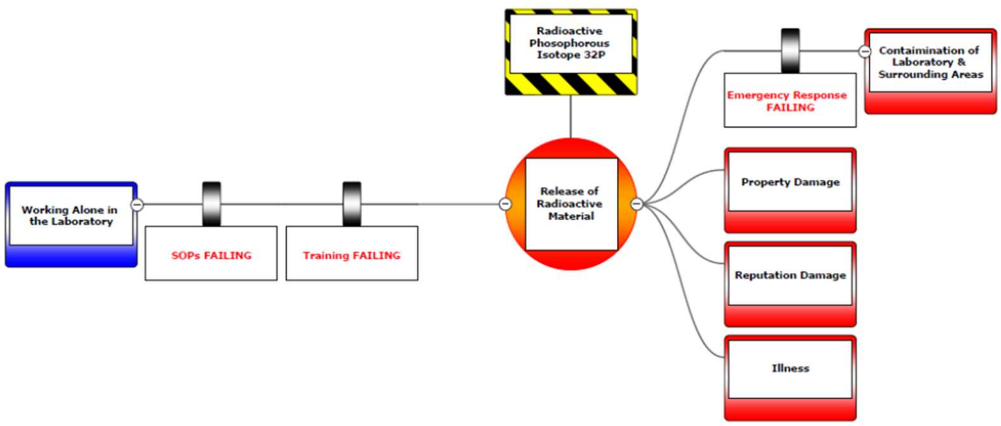

Figure 18. Bowtie of radioactive material contamination incident.

Discussion. This incident showed that the University of Missouri in Columbia, Missouri, had inadequate workplace regulations for the laboratories where the radioactive material was processed. The first issue of this case is that had the radiation worker, who was working alone at the laboratory, not voluntarily reported the contamination incident, the contamination could have spread even further. After the worker was questioned by the health physicist, it was determined that the technician had already left the laboratory room and that the environment had already been contaminated. This was one cause for a delayed and prolonged emergency response. The EHS personnel should have immediately cleared the area instead of spending too much time with questioning the technician. The immediate use of a radiation detector would have provided more reliable results than the statement of the technician. Since the investigation took relatively long, other workers could have potentially been in contact with the radioactive material while it was still ongoing. It was also very unfortunate that the Radiation Safety Officer was off-campus on that day. This slowed down the incident communications and the emergency response.

Case 7: Case study –Incident investigation: Laboratory explosion

A postdoctoral research associate performed a synthesis of hydroxymethylfurfural (HMF) in a thick-walled glass tube that was closed with a Teflon stopper. The objective of the experiment was the conversion of sucrose into hydroxymethylfurfural using silica-sulfuric acid as a catalyst. The synthesis used 500 mg of sucrose, 250 mg of catalyst, 3 mL of sodium chloride solution, and 9 ml of dimethylsulfoxide. The compounds were heated in a thick-walled glass tube with a Teflon screw top. The temperature was 150 °C for 6 h with constant stirring using a magnetic stir bar (200 rpm). A silicone oil bath that was placed on top of a Corning PC 420D hot plate was used for heating the glass tube and its contents. The hot plate was new and had reportedly not been used before. The synthesis was performed in a chemical hood. A similar experiment was placed about 30 cm to the right of the subject synthesis. It used a different hotplate model and a different carbohydrate (cellulose) but was otherwise identical. Fourteen waste containers some of which contained small quantities of flammable organic compounds were placed along the rear wall of the chemical hood. The hood had a posted face velocity of 102 cfm and was recently tested. An explosion took place after 4 hours in the procedure. This resulted in a small fire that involved the hotplate power wire and the silicone oil bath. The post-docs desk was located around the corner, so he was not able to observe the experiment. After the incident, he stated that he frequently checked on the experimental apparatus and the temperature had remained stable at 150 °C. It was later found that the same model of hotplate had overheated at a different university while the heat control was in the off position. Later, the post-doctoral assistant, as well as the principal investigator, stated that they believe that the incident was caused by the malfunctioning hotplate. It was also noted that the EHS department of the university was not involved in chemical safety training for the department (Phifer, 2014).

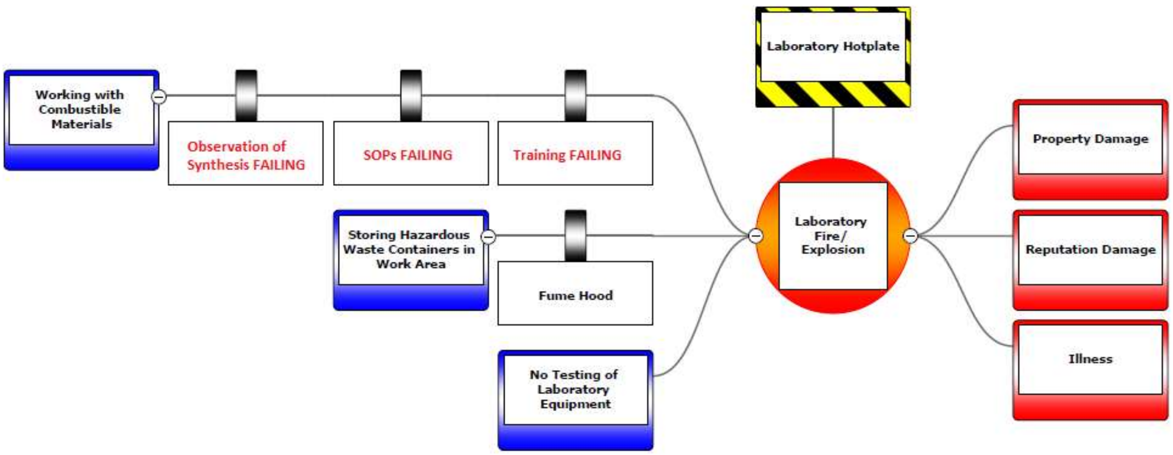

Figure 19. Bowtie of synthesis laboratory explosion incident.

Discussion. Several factors contributed to the laboratory fire and explosion of this case study. The postdoctoral researcher did not observe the synthesis constantly. The personnel either did not receive adequate chemical hygiene training or did not follow best practices because several waste containers were stored in the fume hood, a location where the synthesis apparatus was set up. The hot plate that was used to heat the oil bath was new, but not tested before it was used in the laboratory. It is best practice to test electronic equipment frequently, otherwise it can become a fire hazard. It was later found that a hotplate that was the same model malfunctioned at a different university. For the future, it would be very useful if university facilities that do similar work, for example, chemical laboratory facilities, have a reporting system that provides information about hazardous incidents to other locations.

Case 8: Key Lessons for Preventing Incidents from Flammable Chemicals in Educational Demonstrations

On September 3, 2014, at around 4:00 pm, an educator was performing three variations of the Fire Tornado demonstration for a group of young children at the Terry Lee Wells Nevada Discovery Museum in Reno, Nevada. The basic procedure for all three variations was the same, only the fuel source and color additive were changed: A cotton ball is placed on a glass dish and the fuel, isopropanol or methanol, is added to the dish in order to saturate the cotton ball. Then the color additive, strontium nitrate or boric acid, is added or sprinkled onto the cotton ball. The educator then places the dish on a turntable and the cotton ball is ignited using a barbeque-type butane lighter. The set-up is covered using a wire mesh wastebasket. The educator then spins the turntable which creates the tornado effect. After each fire tornado procedure, the wire mesh basket is removed. The visitors sat on the floor approximately 15 feet away from the demonstration. The first two variations of the demonstration were performed without an incident. During the third variation, the educator held the lighter flame to the cotton ball, but the expected fuel flame did not rise. The educator noticed that methanol fuel had not been added to the cotton ball. The educator attempted to pour a small volume of methanol onto the cotton ball. She poured the amount from a four-liter methanol plastic container. Although there had been no sign of flames from the cotton ball, it is likely that the lighter had ignited the cotton, and it was smoldering. The poured methanol ignited instantly and then flashed back into the four-liter methanol container. This was when the methanol inside the container ignited, resulting in a pressure increase that caused the rise of a large flame from the mouth of the container, which then resulted in a large flash fire. The educator dropped the methanol container after it caught fire and burning methanol spread toward the visitors, some of them caught fire. In response to the fire, two of the museum employees were able to extinguish the fire using a nearby fire extinguisher and a fire blanket. Because of the incident, thirteen people were injured, including eight children and one adult. They were transported to the hospital and one child was kept overnight for medical treatment and additional observation (Chemical Safety Board, 2014).

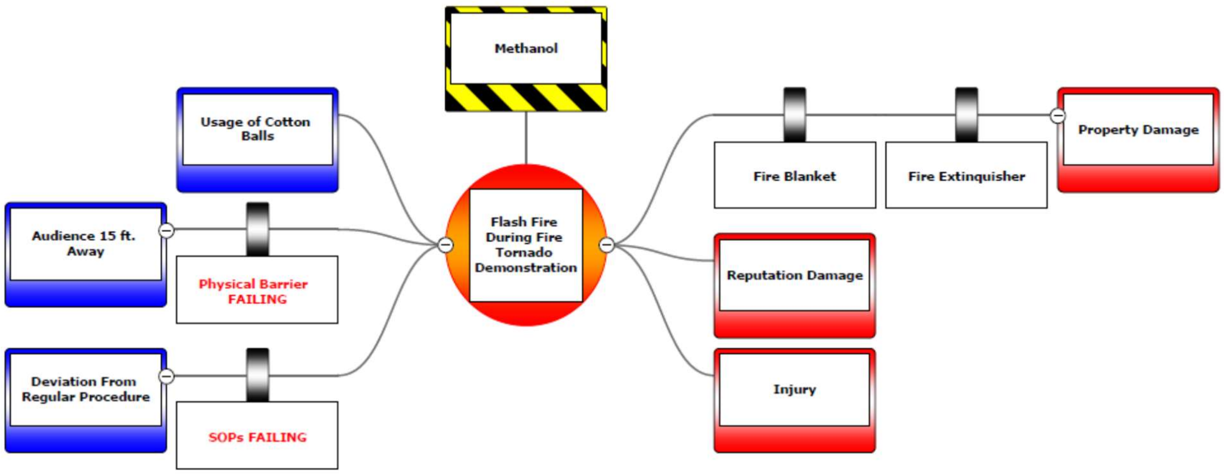

Figure 20. Bowtie of educational demonstration incident.

Discussion. Failing mitigative barriers were the main causes of the incident at the Discovery Museum in Reno, Nevada. There was no physical barrier between the educator who performed the demonstration and the audience. The educator did not have sufficient training, otherwise, they would not have poured the methanol directly from the four-liter storage container. Safety-cans are a convenient and safe way to store and pour flammable solvents. The educator deviated from the regular procedure because they attempted to soak the cotton ball that was left dry in the midst of the procedure. While it was very fortunate that two other employees of the museum were able to extinguish the fire, it is unclear why the educator who had performed the demonstration did not attempt to extinguish the fire.

Case 9: Report to the University of Hawaii at Manoa on the Hydrogen/Oxygen Explosion of March 16, 2016

An incident with devastating consequences occurred at the Manoa campus of the University of Hawaii. At the Hawaii Natural Energy Institute (HNEI), research on renewable energy sources and energy integration is conducted. The laboratory that was involved in the accident focused on using hydrogen, oxygen and carbon dioxide for the green production of biofuels and bioplastics. For this purpose, the laboratory used knallgas bacteria. Those microbes can capture the energy from the reaction between hydrogen and oxygen. The knallgas bacteria were cultured in an open gas system with continuous gas flow. Flow rates for hydrogen, oxygen, and carbon dioxide were controlled by mass flow meters. The gases were mixed rapidly in a gas proportioner and sparged through the bacterial culture. Unused gas exited out of the bioreactor into the fume hood. The laboratory procedure was performed since 2013 using various types of bioreactors at 1-3 atm. The postdoctoral researcher who was involved in the accident came to the laboratory in October 2015 to develop a closed gas system bioreactor for avoiding the waste of gases. She was trained in the preparation of gas mixtures using a 1-gallon pressure vessel. The vessel was used regularly to supply small scale liquid and petri dish bacteria cell cultures at a pressure of 2 atm. The set up was used for 8 months without incidents. The protocol of the experiment as well as necessary changes were discussed in weekly meetings by the principal investigator and the postdoctoral researcher. To streamline the research process using the closed gas system bioreactor, the researchers decided to scale-up the procedure by pre-mixing the gases in a new 13-gallon storage tank. A risk analysis for using the tank with hydrogen and oxygen was not documented. The tank arrived in December 2015 and was leak-tested in January of 2016. From the beginning of February until March 16, 2016, the gas storage tank was filled eleven times with the gas mixture. Each filling contained gas mixtures in the explosive range with pressures from 37 to 117 psi. The PI and post-doctoral researcher assumed the process to be safe since they stayed well below the maximum pressure for the storage tank (140 psi). A laboratory inspection was performed in January 2016; however, the use of gas storage tanks was not questioned because the inspection used a standardized checklist for chemical laboratories. Items for the inspection were chemical waste, gas cylinder storage, laboratory fume hood certification, documentation, and training. On the day before the accident, the postdoctoral research noticed a “cracking sound” inside of the 1-gallon pressure vessel. She reported this to her principle investigator. This occurred when the postdoctoral researcher depressed the on/off button of the vessel’s digital gauge. As she opened the vessel, the researcher found the Petri dishes cracked inside. The gauge had been added to the experimental set-up in February 2016 because it had a smaller error range than the previous gauge. The gauge was not rated as intrinsically safe. After she had reported the incident to the primary investigator, he strongly advised her not to use the vessel again. On March 16, 2016, the post-doctoral researcher had filled the 13-gallon gas storage tank for the eleventh time and was ready to reconnect it to the bioreactor. As she pushed the On/Off button of the pressure gauge on the tank, it exploded and caused severe injuries to the postdoctoral researcher and caused extensive damage to the laboratory, the adjacent laboratories, and the hallways. The pressure gauge on the gas storage tank was of the same model as the one that had previously malfunctioned for the 1-gallon vessel. Weeks before the accident, the postdoctoral researcher had also reported being electrically shocked when touching the pressure vessel of the gas tank. There were no blast barriers and the researcher did not wear any type of personal protective equipment during the time of the incident. After this incident, UH Manoa established a safety committee to review experiments that involve highly hazardous substances or processes. The committee is faculty-led and consists of EHS personnel and experienced faculty members who have knowledge in various sectors.

Furthermore, HNEI created a laboratory safety walkthrough guide to assist researchers with laboratory safety compliance (Merlic, Ngai, Schroeder & Smith, 2016).

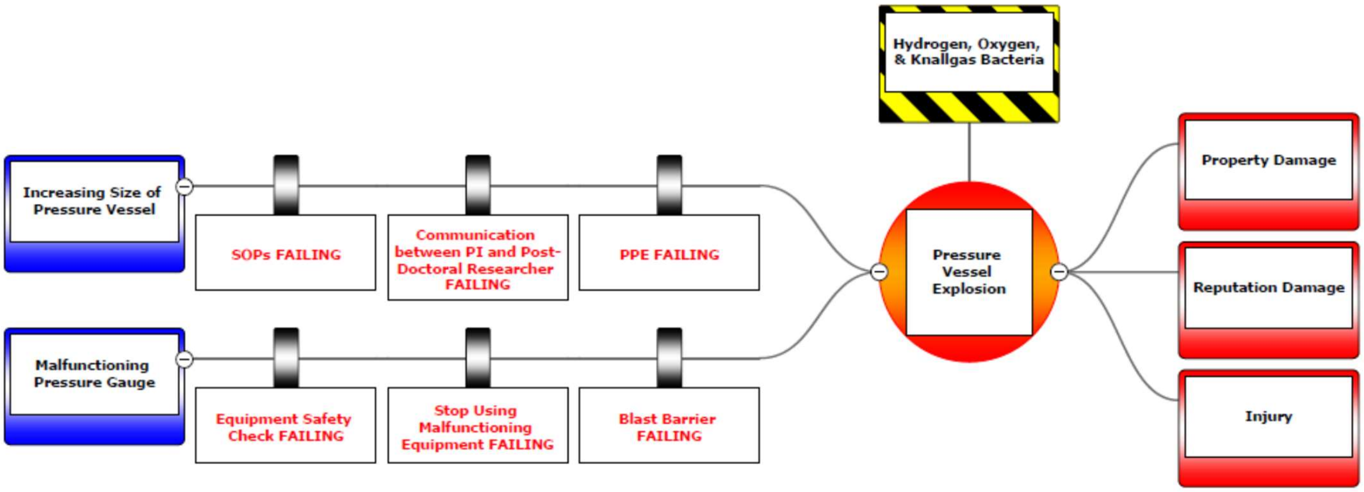

Figure 21. Bowtie of University of Hawaii incident.

Discussion. For the researchers at the Hawaii National Energy Institute, it would have been especially important to do an extensive risk assessment and to implement barriers that are effectively protecting the workers from the hazards posed by hydrogen, oxygen, and the knallgas bacteria. They should have checked and performed maintenance on the pressure vessels frequently. Ignoring the fact that a cracking sound was noticeable and broken Petri dishes were found inside one day before the incident occurred should have been enough reason to stop using all of the vessels that were the same model. The postdoctoral had reported that she had been electrically shocked when she touched the pressure vessel that exploded later for the incident. It is unclear if the postdoctoral researcher failed to inform the principal investigator of the issues or if they both made the wrong assumption that it was safe to continue with the processes that involved using the pressured vessel. There were no blast barriers in the laboratory and the postdoctoral researcher did not wear proper personal protective equipment while the explosion occurred. These are two examples of failing mitigative barriers. Another notable issue for this case was that a previously performed laboratory safety inspection did not involve a review of the work processes that used pressured vessels. They had used a standardized check-list for the audit which did not include questions about the pressurized storage tanks. A standard operating procedure should be composed for every method that is performed at laboratory locations. This collection of documents, which usually includes safety data sheets, certificates of analysis, manuals for the equipment, and records about calibrations and maintenance, can serve as a good basis for a job hazard analysis. When the risk is unacceptably high, effective hazard controls need to be implemented immediately.

Case 10: Case study – A two-liter pyridine spill in an undergraduate laboratory

An incident occurred on the Tuesday before Thanksgiving at Augustana University in Sioux Falls, South Dakota. On that day, three laboratory sessions were held: Medicinal Chemistry, General Chemistry, and Organic Chemistry. A student who was enrolled in Medicinal Chemistry and who had been a stockroom assistant for more than a year walked through the organic chemistry laboratory to the chemical stockroom. He wanted to retrieve 10 mL of pyridine for his experiment. He put the four-liter bottle down at an angle on a benchtop in the stockroom. This was when the bottle cracked in half diagonally. Two liters were spilled onto the student, the benchtop and the floor of the stockroom. He tried to call for help several times, but nobody responded. He eventually caught the attention of the organic chemistry instructor and two senior lab assistants. One of the lab assistants later stated that the student seemed to be disoriented maybe due to the pyridine vapors. Before anyone was able to help him, the student proceeded down the hallway and down the stairs to a private shower, where he took off his clothes and then washed the affected areas with water. Two male faculty members were there in less than a minute and assisted the student. The student initially stated that the affected skin felt a little ‘‘strange’’, but after the shower, he stopped feeling any discomfort. The student also said he felt nauseated right after the spill happened, but after one day, he felt no ill effects. The student was brought to a local hospital, where a physician examined him and he and was deemed to be physically unaffected. He was prescribed antibiotics and moisture cream for the affected skin areas. The student was monitored over Thanksgiving break and showed no acute health effects from the exposure to the pyridine. While the student was assisted, the situation at the location evolved as followed: Since the student exited through the organic chemistry lab, the whole class was aware of what happened, and the students quickly evacuated. However, the instructor and the students of the general chemistry lab were not aware of the situation for some time, even though the students had begun to smell the pyridine and became nauseated.

The instructor left the student assistants in charge and went to assist the situation. Due to the smell, the student moved to the other side of the room. They did not want to leave without their instructor. The students continued to be nauseated by the smell and were then evacuated from the room. At first, the stockroom manager tried to contain the spill with sodium bicarbonate but could not finish the task because of the intense smell of the pyridine. People in other parts of the building started to smell the pyridine and were evacuated within 15 minutes. Even though the faculty had experience with spill clean-ups, they were not able to clean up the spill because it was too large. The Sioux Falls Fire Department Hazardous Materials Team was called to investigate and help with the cleanup. Because they had not encountered a pyridine spill before, they were very cautious and heavily relied on the knowledge of the chemistry faculty. The pyridine spill was 4 feet in diameter. The laboratory fume hood was left on and the windows of the chemical stockroom were opened. After a few moments, the Hazardous Materials Team concluded that using electronic sensors, the concentration of volatile organic compounds (VOC's) was low enough to enter the room. It was determined that the best solution was to let the ventilation system of the science building take care of the vapor over the Thanksgiving break. After returning from Thanksgiving break, it was recognized that there was very little odor in the building, and it was safe to resume normal operations. The only remaining issue was the amount of pyridine that was bound to the sodium bicarbonate matrix. There was initially no plan for who would clean up the spill. A faculty member with an auto-immune disease cleaned up the spill together with two other faculty members. They felt fine initially but became nauseated after a few hours and went home for the day. A follow-up safety committee meeting was called and the incident, as well as protocol changes, were discussed. As a summary, the author mentioned that pyridine was not particularly dangerous and just the intense smell was the reason for the evacuation of the building (Eichler, 2016).

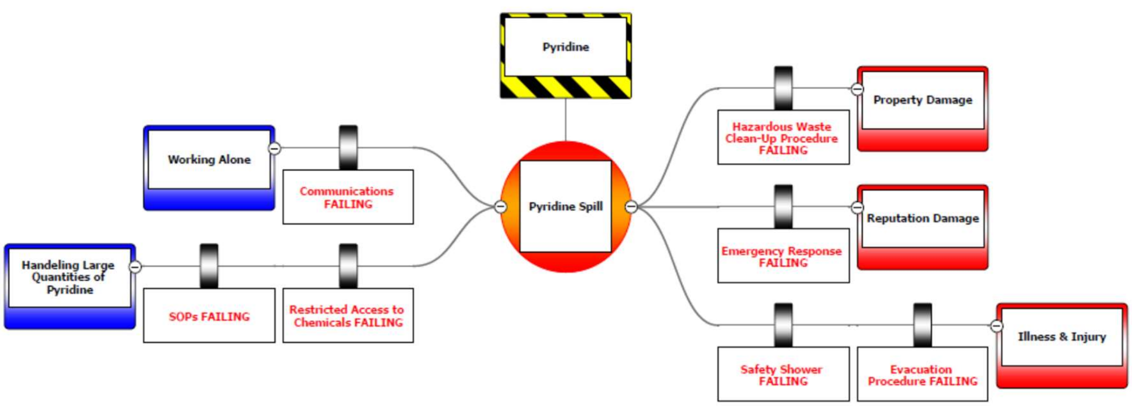

Figure 22. Bowtie of pyridine spill incident.

Discussion. Pyridine is a suspected human carcinogen and can have severe short-term and long-term health effects. The substance can influence the central nervous system and a self-contained breathing apparatus is recommended for the handling of pyridine. The OSHA time-weighted average is 5 ppm (15 mg/m^3). Pyridine is a highly flammable substance and an environmental toxin (Pubchem, n. d.). The author made the wrong assumption that pyridine was not particularly dangerous at the end of the publication. Several of the people that were involved in the incident seemed to have a similar opinion. A student, who also was as a stockroom assistant, had unrestricted access to chemicals and handled large amounts of pyridine. He was alone in the laboratory while the spill occurred. It took several minutes until the incident was noticed and medical assistance was provided. The student used a safety shower that was located relatively far from the laboratory. Not all students evacuated the building immediately because the students and the faculty member that were in session for the general chemistry laboratory were not notified. When those individuals started to smell the pyridine, the instructor left the student assistants in charge and only after a prolonged exposure to the chemical, the group was evacuated. The whole building was evacuated after 15 minutes. Meanwhile, the stockroom manager attempted to clean up the spill and noticed it was too large. The windows of the laboratory were opened which could have introduced additional oxygen that could have served as a fuel source if there had been a fire. This situation clearly shows that Augusta University did not have an adequate alarm system and emergency response plan. As the fire department arrived, it had to rely on the knowledge of the chemistry faculty. Information about CAS-registered chemicals is nowadays readily available because manufacturers are required to provide safety data sheets of their products. Pyridine is an EPA-regulated substance; therefore, it was a very questionable decision to have it evaporate over the holidays. The faculty member with the autoimmune disease should not have cleaned up the residues of the chemical that were still found after the Thanksgiving weekend. Augusta University should have instead communicated the remaining issue to the local authorities so that a coordinated cleanup, performed by trained hazardous material technicians, could have been initiated.

Case 11: Case study: Reaction scale-up leads to incident involving bromine and acetone

This publication describes an incident that was caused by a reaction scale-up involving acetone and bromine. An experienced postdoctoral researcher modified a published procedure for the deintercalating sodium from a metal oxide. He included the use of acetone in a final workup step. The published procedure called for the preparation of a fresh 6 M bromine solution in acetonitrile. The starting material that consisted of sodium, cobalt and antimony oxides was combined with the bromine/ acetonitrile mixture. After 24 hours of stirring, the substrate was vacuum filtered through a Buchner funnel and washed several times with water. The scale for the procedure usually consisted of 500 to 800 mg of solid substrate and 16 mL of the bromine/ acetonitrile mixture. The new washing step involved 5-8 mL of acetone instead of water. The researcher did this several times without any incident. Due to the success of this protocol, the researcher scaled up the experiment. He was working inside of a fume hood whose sash was at the maximum recommended operation height of about 18 inches. He mixed 3 g of the solid substrate with 15 mL of 6M bromine/acetonitrile mixture. During the first attempt, as soon as he added the acetone to the mixture on the Buchner funnel, the content on the vacuum flask reacted violently which resulted in an expulsion of gases and liquids on the body of the researcher and the surrounding areas. The content of the vacuum flask sprayed on the hands, arms, torso, and face of the researcher. He was wearing a flame-resistant laboratory coat, safety glasses, and nitrile gloves when the incident occurred. After the researcher was exposed to the mixture, he removed the laboratory coat and the long-sleeved shirt. He went to the nearest safety shower and briefly rinsed off without removing other clothing. Due to the fumes, the researcher proceeded to an eye wash station in an adjacent laboratory. A graduate student assisted the researcher while he was rinsing his face and eyes for 10 to 12 minutes. The standard protocol called for at least 15 minutes. The researcher did not appear to have chemical exposure to any skin areas besides his face. The liquid had sprayed on his face and run under the safety glasses into both eyes. He was taken to the hospital and treated for first degree burns. He was released on the same day. The incident happened on a Friday. After a follow-up medical examination on the following Monday, he was cleared to return to work (Chance, 2016).

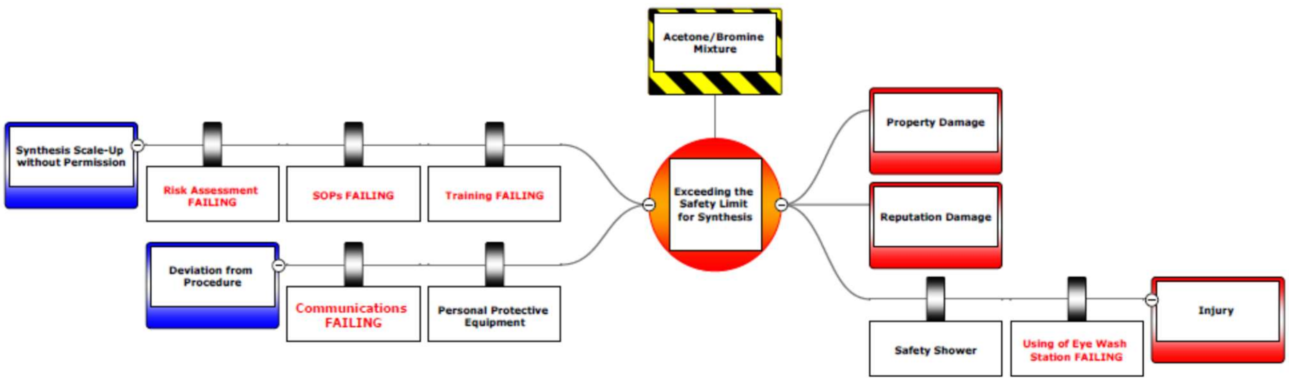

Figure 23. Bowtie of bromine/acetone incident.

Discussion. This incident is very similar to the first case that was discussed in this chapter. A synthesis that involved acetone and bromine was scaled up, the mixture reacted violently, and gases and liquids were expulsed on the researcher and the surrounding areas. The intentional scale-up of the synthesis was a deviation from the standard protocol that cannot be justified by the effectiveness of the procedure. The researcher was wearing proper personal protective equipment and used a safety shower immediately after the incident. However, he went to an adjacent laboratory and used the eyewash station there. It can be assumed that there had not been a functioning eyewash station in the laboratory room where the incident had occurred. The researcher did not comply with the standard protocol of rinsing the eyes for at least 15 minutes. A potential solution to prevent similar accidents could be restricting access to chemicals. If the substances are in a centralized storage area, it could be arranged that the researchers are just able to request the amounts of chemicals that were official approved by a chemical safety committee. If changes for a procedure are proposed, a new risk assessment needs to be performed. Changes to a procedure should not be made because one person assumed it was safe.

Conclusion

The results of this comparative case study research project show that academic and primary educational laboratory facilities need to improve in the areas of training, risk management, and communication. Table 5 displays an overview of failing barriers for the eleven cases included to the project. Most of the facilities had deficiencies for training, SOPs, engineering controls, and emergency response. Failing communications and a lack of equipment monitoring were common themes as well.

Table 5. Overview of failing barriers for all cases.

Case	FAILING - Engineering Control	FAILING - Restricted Access to Chemicals	FAILING - Restricted Access to Laboratory	FAILING - SOPs	FAILING - Equipment Monitoring	FAILING - Risk Assessment	FAILING - Emergency Response	FAILING - Communications	FAILING - Training	FAILING - Personal Protective Equipment
1		x	x	x					x	
2	x			x			x	x	x	
3									x	
4					x					
5				x		x				x
6				x			x		x	
7				x	x				x	
8	x			x						
9	x				x			x		x
10	x	x		x			x		x	
11				x		x	x	x	x	
Total	4	2	1	8	3	2	4	3	7	2

For any facilities, it is important to do a risk assessment before starting a new experiment or doing any alterations to the standard protocol. The visual method of the bowtie can serve as a tool to illustrate undesired incidents in the chemistry laboratory. It makes it very easy to mind-map possible threads and consequences around the top event that can be caused by a hazard present in the laboratory. Non-functional barriers can create several paths that can lead to an undesired incident. Potential threats can come from multiple sources and can therefore not be controlled with a linear risk management model. The bowtie diagram, in fact, shows that hierarchical models of risk management are not very accurate for fluid work environments. Barriers that include administrative controls, engineering controls, and personal protective equipment can fail. Work processes that are frequently changing call for risk management concept that can adjust if the dynamics of the system require it. When there is no written standard operating procedure, people will make decisions based on assumptions and memorization, and not on facts. This can have horrific consequences. A certain standard for laboratory procedures needs to be established. The standard operating procedure then serves as a guideline for people that are learning the methodology. At the same time, an experienced technician, staff member, or the principal investigator for the research project needs to observe the trainee while they are performing the method for the first few times. As soon as a working routine was established, the trainee may perform the procedure but has to communicate if they need to make an adjustment or alteration of the method, since this may require additional risk controls. However, safety training and SOPs that are implemented as barriers can only be effective when the employees have a positive attitude towards safety and will follow the rules and regulation in all situations. It was already discussed in the literature that human error is too often identified as the cause of undesired incidents. Rather than focusing on the "sharp end" (work level) of the risk management framework, the whole system needs to be monitored and communications between the different levels of the work hierarchy need to be improved (Dallat, Salmon & Goode, 2017). An excellent way to improve communications for an organization or institution is establishing safety committees that include representatives from all work levels. During their frequent meetings, experts and professionals working at the different areas of the organization can discuss safety concerns and evaluate procedures. The goal is to keep safety a priority and to effectively communicate knowledge about hazards and risks. Ultimately, it might be possible to create a generative safety culture at educational and academic institutions.

Recommendations

While educational and academic institutions display the characteristics of a business in many aspects of their operations, they are not able to compete with businesses and industries when it comes to occupational health and safety. Safety education and training of students, faculty, and staff who are present at the laboratories of the primary educational facilities and academic institutions, need to be improved significantly. All people need to develop a proactive mindset and a positive attitude toward safety. Over time, this will not only reduce the frequency of undesired hazardous events and be more cost-efficient but, will also help to create a generative safety culture for the next generation. Undesired incidents can provide learning opportunities and it is very important that subsequent investigations not only focus on the mistakes that were made at the work level but also how the risk management framework failed to adapt to the unexpected situations. What students learn about safety during the years of their education will also later benefit the people they are collaborating with as professionals. This requires independent and proactive thinking as well as a general awareness of the work situation and the surroundings. The first step must be that administrators, educators, and students, acknowledge that there cannot be a single guideline that covers all the hazards and risks that are associated with chemicals and laboratory work practices. In order to become more effective learning environments for the next generation new teaching methods on how to successfully incorporate safety training to the curriculum need to be explored. All people that are involved in the processes at the facilities need to gain knowledge about the different aspects of occupational safety. They need to include safe practices as an integral part of their daily work routine. This can be accomplished by making safety a core component of the curriculum and an evaluation requirement for both educators and students. Submitting a Job Hazard Analysis together with their laboratory reports and research proposals would provide students with the opportunity to gain more knowledge in safe laboratory practices. As they gain experiences, students will eventually become confident and are going to be able to evaluate hazardous situations in an informed manner. At the same time, procedures being performed at research and teaching laboratories should be observed by trained safety professionals. They can then make recommendations on how to implement or adjust safety barriers. This will not guarantee that zero incidents happen in the future. However, if safety becomes a core value of the academic and educational world, undesired incidents will hopefully become very rare occurrences.

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APPENDIX

LABORATORY INCIDENTS JANUARY 2001–JULY 2018

U.S. Chemical Safety and Hazard Investigation Board

20 Years of Driving Chemical Safety Change 1998 2018

CSB U.S. Chemical Safety and Hazard Investigation Board

The U.S. Chemical Safety Board's (CSB) laboratory dataset includes chemical incidents that occurred in public and private laboratories from January 2001 through July 2018. The incidents occurred in a variety of organizations and settings, including private research laboratories, universities, high schools, middle schools, elementary schools, the National Laboratories, state-run laboratories and educational demonstrations. The CSB receives incident information from multiple sources, including the media and the U.S. Coast Guard's National Response Center. Not all incidents undergo secondary verification by the agency. Additional laboratory incidents may have occurred during this period but have not been identified by the CSB.

Date Prepared: August 16, 2018

Incident Date	Organization	City	State	Fatalities	Injuries
2001-07-23	University of California, Irvine	Irvine	California	0	3
2001-10-10	University of Utah	Salt Lake City	Utah	0	0
2001-10-12	Genoa-Kingston High School	Genoa	Illinois	0	7
2001-10-16	U.S. Army Research Laboratory	Adelphi	Maryland	0	1
2002-01-08	Los Alamos National Laboratory	Los Alamos	New Mexico	0	0
2002-03-11	New Berlin West High School	New Berlin	Wisconsin	0	1
2002-12-31	University of Washington Medical Center	Seattle	Washington	0	0
2004-01-30	Federal Way High School	Federal Way	Washington	0	2
2005-06-18	Huntington Beach High School	Huntington Beach	California	0	2
2006-01-23	Western Reserve High School	Hudson	Ohio	0	4
2006-01-24	Lansing Community College	Lansing	Michigan	0	0
2006-01-26	Middle Township High School	Cape May County	New Jersey	0	5
2006-01-31	Cornell University	Ithaca	New York	0	1
2006-02-20	West Chester University	West Chester	Pennsylvania	0	2
2006-02-24	University of Denver	Denver	Colorado	0	0
2006-03-02	University of Idaho	Moscow	Idaho	0	1
2006-03-07	Saratoga Springs High School	Saratoga Springs	New York	0	8
2006-03-12	Monahans High School	Monahans	Texas	0	3
2006-04-03	University of Maryland Biotechnology Institute	Baltimore	Maryland	0	1
2006-04-11	Southwest Minnesota State University	Marshall	Minnesota	0	1
2006-04-20	Scripps Research Institute	Jupiter	Florida	0	0
2006-04-21	Northwestern University	Evanston	Illinois	0	1
2006-05-05	Massachusetts Institute of Technology	Cambridge	Massachusetts	0	0
2006-05-09	Prosper High School	Dallas	Texas	0	1
2006-05-16	Georgia Institute of Technology (Georgia Tech)	Atlanta	Georgia	0	1
2006-06-08	Lafayette High School	James City	Virginia	0	1
2006-06-16	Binghamton University	Vestal	New York	0	0

Laboratory Incidents January 2001–July 2018

U.S. Chemical Safety and Hazard Investigation Board

20 Years of Driving Chemical Safety Change 1998 2018

CSB U.S. Chemical Safety and Hazard Investigation Board

Incident Date	Organization	City	State	Fatalities	Injuries
2006-06-28	Purdue University	West Lafayette	Indiana	0	0
2006-07-03	Cardiovascular Genetics	Salt Lake City	Utah	0	1
2006-07-09	Washington Middle School	Aurora	Illinois	0	0
2006-07-20	University of Colorado	Boulder	Colorado	0	3
2006-07-20	University of Minnesota, Twin Cities	St. Paul	Minnesota	0	0
2006-07-27	University of Colorado	Boulder	Colorado	0	1
2006-08-01	University of Washington	Seattle	Washington	0	1
2006-08-16	Virginia Tech	Blacksburg	Virginia	0	3
2006-08-24	Rice University	Houston	Texas	0	0
2006-08-27	Indiana University	Bloomington	Indiana	0	0
2006-09-06	Georgia State University	Atlanta	Georgia	0	6
2006-10-03	Hasbrouck Heights High School	Hasbrouck Heights	New Jersey	0	0
2006-10-10	Oakland High School	Oakland	Oregon	0	0
2006-10-11	Morrisville Pharmacy	Morrisville	Pennsylvania	0	1
2006-10-31	Louisiana State University	Baton Rouge	Louisiana	0	2
2006-11-01	Eastern Guilford High School	Greensboro	North Carolina	0	0
2006-11-03	University of Kentucky	Lexington	Kentucky	0	7
2006-11-12	Yale University	New Haven	Connecticut	0	1
2006-12-03	Clinical Pathology Labs	Springville	Utah	0	1
2006-12-19	Oak Ridge National Laboratory	Oak Ridge	Tennessee	0	0
2006-12-21	University of Arkansas	Fayetteville	Arkansas	0	0
2007-01-17	Pennsylvania State University	State College	Pennsylvania	0	0
2007-01-18	South Fremont High School	Saint Anthony	Idaho	0	0
2007-02-01	H.B. du Pont Middle School	Hockessin	Delaware	0	1
2007-02-07	Mead Middle School	Mead	Washington	0	2
2007-02-09	Dobyns-Bennett High School	Kingsport	Tennessee	0	0
2007-02-20	James Madison University	Harrisonburg	Virginia	0	0
2007-02-26	Duquesne University	Pittsburgh	Pennsylvania	0	0
2007-03-20	Boston College	Boston	Massachusetts	0	1
2007-03-27	North Carolina State University	Raleigh	North Carolina	0	1
2007-03-30	Frontier Scientific	Logan	Utah	0	1
2007-04-10	West Virginia University	Morgantown	West Virginia	0	3
2007-04-30	Volusia County Health Department	Daytona Beach	Florida	0	1
2007-05-01	University of Wisconsin, Milwaukee	Milwaukee	Wisconsin	0	0

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Laboratory Incidents January 2001–July 2018

1998 2018 Years of Driving Chemical Safety Change

CSB U.S. Chemical Safety and Hazard Investigation Board

U.S. Chemical Safety and Hazard Investigation Board

Incident Date	Organization	City	State	Fatalities	Injuries
2007-05-07	CEMEX	Brooksville	Florida	0	1
2007-05-22	Aspen Medical Clinic	Maplewood	Minnesota	0	1
2007-05-24	University of Pittsburgh	Pittsburgh	Pennsylvania	0	1
2007-05-28	University of South Florida	Tampa	Florida	0	3
2007-05-30	Texas A&M University	College Station	Texas	0	0
2007-06-05	Rensselaer Polytechnic Institute	Troy	New York	0	3
2007-06-18	Delaware State University	Dover	Delaware	0	2
2007-07-18	Tennessee Technological University	Cookville	Tennessee	0	1
2007-07-27	University of Arizona	Tucson	Arizona	0	0
2007-08-03	State University of New York at Buffalo	Getzville	New York	0	0
2007-08-06	Washington University in St. Louis	St. Louis	Missouri	0	0
2007-08-10	Georgia Institute of Technology (Georgia Tech)	Atlanta	Georgia	0	1
2007-08-15	Rich Products Corporation	Morristown	Tennessee	0	2
2007-09-11	Ball State University	Muncie	Indiana	0	0
2007-09-11	University of Florida	Gainesville	Florida	0	0
2007-09-11	University of Vermont	Burlington	Vermont	0	15
2007-09-16	ASTEC Charter Middle School	Oklahoma City	Oklahoma	0	2
2007-09-17	University of Michigan	Ann Arbor	Michigan	0	0
2007-09-19	Purdue University	West Lafayette	Indiana	0	0
2007-10-01	Boston University	Boston	Massachusetts	0	0
2007-10-08	Oakwood College	Huntsville	Alabama	0	3
2007-10-14	University of California, Santa Barbara	Santa Barbara	California	0	0
2007-10-19	Marshall University	Huntington	West Virginia	0	0
2007-10-25	Yale University	New Haven	Connecticut	0	1
2007-10-29	Drake University	Des Moines	Iowa	0	0
2007-10-30	Northwestern University	Evanston	Illinois	0	0
2007-11-11	State of Illinois Police Crime Laboratory	Springfield	Illinois	0	0
2007-11-16	Granite Hills High School	Apple Valley	California	0	1
2007-11-27	University of North Carolina	Chapel Hill	North Carolina	0	2
2007-12-06	Brigham Young University	Provo	Utah	0	0
2007-12-19	T2 Laboratories, Inc.*	Jacksonville	Florida	4	14
2008-01-15	Craig Middle School	Craig	Colorado	0	8
2008-01-16	Somers High School	Somers	New York	0	8
2008-01-22	Fairhaven High School	Fairhaven	Massachusetts	0	0

Incident Date	Organization	City	State	Fatalities	Injuries
2008-02-01	Dickinson High School	Dickerson	North Dakota	0	0
2008-02-05	University of Washington	Seattle	Washington	0	0
2008-02-13	Southern Illinois University	Carbondale	Illinois	0	0
2008-02-13	University of South Dakota	Vermillion	South Dakota	0	0
2008-02-19	Johns Hopkins University	Baltimore	Maryland	0	0
2008-02-22	University of Wisconsin, Madison	Madison	Wisconsin	0	0
2008-03-05	Johns Hopkins University	Baltimore	Maryland	0	2
2008-03-30	University of Texas	Austin	Texas	0	0
2008-04-04	Western Middle School	Greenwich	Connecticut	0	0
2008-04-07	University of Washington	Seattle	Washington	0	0
2008-04-10	Florida A&M University	Tallahassee	Florida	0	1
2008-05-13	Vintage High School	Vallejo	California	0	0
2008-05-19	Huntington Park College-Ready Academy High School	Huntington Park	California	0	2
2008-05-21	Hudson High School	Hudson	Ohio	0	1
2008-05-21	Mountain View High School	Bend	Oregon	0	0
2008-05-21	University of South Florida	Tampa	Florida	0	6
2008-05-27	University of Arizona	Tucson	Arizona	0	0
2008-06-11	Massachusetts Institute of Technology	Cambridge	Massachusetts	0	1
2008-06-12	University of Florida	Gainesville	Florida	0	0
2008-06-23	University of California, Davis	Sacramento	California	0	2
2008-06-24	Freemont High School	Freemont	California	0	0
2008-07-16	University of Colorado	Boulder	Colorado	0	0
2008-07-22	Colorado State University	Fort Collins	Colorado	0	0
2008-08-08	Auburn University	Auburn	Alabama	0	0
2008-08-11	Canisius College	Buffalo	New York	0	0
2008-09-08	Lewisville High School	Lewisville	Texas	0	0
2008-09-08	Michigan State University	East Lansing	Michigan	0	0
2008-09-08	University of Alabama	Tuscaloosa	Alabama	0	1
2008-09-09	Central Coast Pathology	San Luis Obispo	California	0	3
2008-09-09	Clark Atlanta University	Atlanta	Georgia	0	0
2008-09-12	Trinity College	Hartford	Connecticut	0	1
2008-09-15	California State University, Chico	Chico	California	0	0
2008-09-16	University of Southern Maine	Gorham	Maine	0	4
2008-10-28	Penobscot Bay Medical Center	Rockport	Maine	0	2

LABORATORY INCIDENTS JANUARY 2001–JULY 2018

U.S. Chemical Safety and Hazard Investigation Board

Incident Date	Organization	City	State	Fatalities	Injuries
2008-12-29	University of California, Los Angeles	Los Angeles	California	1	0
2009-02-28	Boise State University	Boise	Idaho	0	1
2009-03-09	Florida Medical Clinic	Zephyrhills	Florida	0	0
2009-07-27	Wasatch Labs	Ogden	Utah	0	3
2009-08-29	Eurand America, Inc.	Vandalia	Florida	0	2
2009-09-08	Indiana University-Purdue University Indianapolis	Fort Wayne	Indiana	0	1
2010-01-07	Texas Tech University*	Lubbock	Texas	0	1
2010-05-11	Texas A&M University	College Station	Texas	0	2
2010-06-02	Southern Illinois University	Carbondale	Illinois	0	1
2010-06-28	University of Missouri	Columbia	Missouri	0	4
2010-12-03	Northwestern University	Evanston	Illinois	0	1
2011-01-17	Spectrum Microwave	Marlborough	Massachusetts	0	20
2011-02-08	SynQuest Laboratories	Alachua	Florida	0	1
2011-02-17	Oregon Health and Science University	Portland	Oregon	0	4
2011-03-08	Southfield Lathrup High School	Lathrup Village	Michigan	0	3
2011-03-10	Louisiana State University	Baton Rouge	Louisiana	0	1
2011-03-16	Choice Dental Laboratory	St. Joseph	Michigan	0	1
2011-04-26	Agilent Technologies	Santa Rosa	California	0	1
2011-04-30	Aberdeen Proving Ground Laboratory	Aberdeen	Maryland	1	0
2011-04-30	Front Range Community College	Longmont	Colorado	0	1
2011-05-02	IMANNA Laboratory, Inc.	Rockledge	Florida	0	1
2011-05-09	University of California, Berkeley	Berkeley	California	0	1
2011-05-12	Clarkson University	Potsdam	New York	0	1
2011-05-18	Louisiana State University	Baton Rouge	Louisiana	0	0
2011-06-20	Purdue University	West Lafayette	Indiana	0	6
2011-06-25	Boston College	Chestnut Hill	Massachusetts	0	1
2011-07-12	University of West Florida	Pensacola	Florida	0	2
2011-07-20	New Life Worship Center	Smithfield	Rhode Island	0	4
2011-08-02	Bradley University	Peoria	Illinois	0	0
2011-08-17	University of Pittsburgh	Pittsburgh	Pennsylvania	0	1
2011-09-02	Membrane Technology and Research, Inc.	Menlo Park	California	1	1
2011-09-12	Geomet Technologies, LLC	Gaithersburg	Maryland	0	1
2011-09-19	Harold L. Richards High School	Oak Lawn	Illinois	0	1
2011-09-21	West Charlotte High School	Charlotte	North Carolina	0	1

LABORATORY INCIDENTS JANUARY 2001–JULY 2018

20 Years of Driving Chemical Safety Change 1998 2018

CSB U.S. Chemical Safety and Hazard Investigation Board

U.S. Chemical Safety and Hazard Investigation Board

Incident Date	Organization	City	State	Fatalities	Injuries
2011-09-26	University of Maryland	College Park	Maryland	0	2
2011-09-27	University of Connecticut Health Center	Framingham	Connecticut	0	2
2011-10-11	University of Florida	Gainesville	Florida	0	1
2011-10-14	Texas Tech University	Lubbock	Texas	0	0
2011-10-17	University of Florida	Gainesville	Florida	0	1
2011-10-20	DeKALB Molded Plastics	Butler	Indiana	0	0
2011-10-24	University of Arizona	Tucson	Arizona	0	0
2011-10-24	University of California, Los Angeles	Los Angeles	California	0	0
2011-10-25	E.E. Smith High School	Fayetteville	North Carolina	0	6
2011-10-26	Kerr Middle School	Del City	Oklahoma	0	1
2011-10-27	Texas Tech University	Lubbock	Texas	0	0
2011-11-30	Bocchi Laboratories	Santa Clarita	California	0	2
2011-12-01	Maple Grove High School	Maple Grove	Minnesota	0	4
2011-12-21	University of Oregon	Eugene	Oregon	0	1
2012-01-09	Scripp Research Institute	La Jolla	California	0	3
2012-01-11	Carnegie Mellon University	Pittsburgh	Pennsylvania	0	0
2012-01-11	University of Florida	Gainesville	Florida	0	1
2012-01-13	David Douglas High School	Portland	Oregon	0	11
2012-01-30	University of Cincinnati	Cincinnati	Ohio	0	1
2012-01-30	University of Wisconsin, Madison	Madison	Wisconsin	0	1
2012-02-06	South Carolina State University	Orangeburg	South Carolina	0	6
2012-03-15	University of Florida	Gainesville	Florida	0	1
2012-03-19	Reedsburg Area High School	Reedsburg	Wisconsin	0	3
2012-03-20	University of Colorado	Boulder	Colorado	0	1
2012-04-11	General Motors Technical Center	Warren	Michigan	0	1
2012-04-12	Mililani High School	Mililani	Hawaii	0	1
2012-04-22	Soule Road Middle School	Liverpool	New York	0	4
2012-05-03	Midwest High School	Natrona	Wyoming	0	1
2012-05-14	Colorado State University	Fort Collins	Colorado	0	1
2012-06-29	Ventura Foods	St. Joseph	Missouri	0	1
2012-07-02	BAE Systems	Radford	Virginia	0	1
2012-07-10	Monsanto	Ankeny	Iowa	0	1
2012-07-11	University of Minnesota, Duluth	Duluth	Minnesota	0	0
2012-07-19	Organix Inc.	Woburn	Massachusetts	0	1

Laboratory Incidents January 2001–July 2018

U.S. Chemical Safety and Hazard Investigation Board

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CSB U.S. Chemical Safety and Hazard Investigation Board

Incident Date	Organization	City	State	Fatalities	Injuries
2012-07-30	U.S. Geological Survey, Oregon Water Science Center	Portland	Oregon	0	1
2012-10-20	University of Akron	Akron	Ohio	0	5
2012-10-24	Derry Area Schools	Derry	Pennsylvania	0	1
2012-11-12	Eastern High School	Voorhees	New Jersey	0	7
2012-11-19	Monolyte Laboratories, Inc.	Slaughter	Louisiana	0	0
2013-02-01	Clovis North High School	Clovis	California	0	1
2013-02-01	Washington State University	Pullman	Washington	0	1
2013-02-09	Air Liquide America Specialty Gases, LLC	La Porte	Texas	1	1
2013-02-12	Villanova University	Villanova	Pennsylvania	0	10
2013-02-26	Massachusetts General Hospital	Charlestown	Massachusetts	0	1
2013-04-10	Colorado College	Colorado Springs	Colorado	0	13
2013-05-13	Energetic Materials Research and Testing Center	Socorro	New Mexico	0	3
2013-06-04	University of Delaware	Newark	Delaware	0	1
2013-06-17	St. Scholastica Academy	Covington	Louisiana	0	3
2013-09-09	Roach Middle School	Frisco	Texas	0	3
2013-10-03	Chapel Hill High School	Chapel Hill	Georgia	0	1
2013-10-09	Dow Chemical Company	North Andover	Massachusetts	1	0
2013-11-01	Syracuse University	Syracuse	New York	0	1
2013-11-12	La Joya Community High School	Avondale	Arizona	0	4
2013-11-12	University of Illinois	Urbana	Illinois	0	5
2013-11-25	Lincoln Park High School	Chicago	Illinois	0	1
2014-01-02	Beacon High School	New York	New York	0	2
2014-01-08	Amgen, Inc.	South San Francisco	California	0	2
2014-01-23	Auburn University	Auburn	Alabama	0	1
2014-02-19	Northside College Prep High School	Chicago	Illinois	0	5
2014-04-09	Tindley Accelerated School	Indianapolis	Indiana	0	1
2014-06-09	Boise State University	Boise	Idaho	0	1
2014-06-17	University of Minnesota, Twin Cities	Minneapolis	Minnesota	0	1
2014-08-20	Bentley Laboratories	Edison	New Jersey	0	2
2014-09-03	Terry Lee Wells Nevada Discovery Museum*	Reno	Nevada	0	13
2014-09-15	STRIVE Preparatory School*	Denver	Colorado	0	4
2014-10-18	University of Rochester	Rochester	New York	0	3
2014-10-20	A Community of Faith Church*	Raymond	Illinois	0	4
2014-10-31	UIC College Prep	Chicago	Illinois	0	2

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Incident Date	Organization	City	State	Fatalities	Injuries
2015-01-06	Newfield High School	Selden	New York	0	1
2015-01-26	Kingsway Regional High School	Woolwich	New Jersey	0	17
2015-02-02	Texas Tech University	Lubbock	Texas	0	4
2015-02-24	Michigan State University	East Lansing	Michigan	0	1
2015-02-28	Sandstone Elementary School	Billings	Montana	0	4
2015-05-15	Apex High School	Apex	North Carolina	0	0
2015-05-22	Lincoln High School	Tallahassee	Florida	0	2
2015-06-20	United Taconite Laboratory	Forbes	Minnesota	0	0
2015-08-25	Southern Illinois University	Carbondale	Illinois	0	1
2015-09-15	University of Akron	Akron	Ohio	0	1
2015-10-30	W.T. Woodson High School	Fairfax	Virginia	0	6
2016-02-05	Slater High School	Slater	Missouri	0	1
2016-02-29	Glendale Community College	Glendale	California	0	2
2016-02-29	University of Rochester	Rochester	New York	0	1
2016-03-09	Texas A&M University	College Station	Texas	0	1
2016-03-10	Texas Tech University	Lubbock	Texas	0	1
2016-03-16	University of Hawaii	Honolulu	Hawaii	0	1
2016-04-27	Hidden Lake High School	Westminster	Colorado	0	1
2017-05-24	Perth Amboy High School	Perth Amboy	New Jersey	0	1
2017-07-07	University of Maryland	College Park	Maryland	0	1
2018-02-26	University of Utah	Salt Lake City	Utah	0	1
2018-02-27	Frontage Laboratories Inc.	Exton	Pennsylvania	1	0
2018-03-27	University of Utah	Salt Lake City	Utah	0	2
2018-05-09	Merrol Hyde Magnet School	Hendersonville	Tennessee	0	10
2018-05-15	Yellow School	Houston	Texas	0	12
2018-05-29	University of Nebraska	Lincoln	Nebraska	0	2
2018-06-30	Boston University	Boston	Massachusetts	0	1
2018-07-17	Norris Labs	Bozeman	Montana	0	0
2018-07-31	Dietary Pro Labs	Wausau	Wisconsin	0	1
2018-08-07	Hanford Nuclear Reservation	Richland	Washington	0	2

* Subject of a CSB investigation.

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Note. From “CSB Releases Laboratory Incident Data (Jan. 2001 - Jul. 2018)” (CSB, 2018).