RESOURCE ARTICLE

Using bowtie methodology to support laboratory hazard identification, risk management, and incident analysis

Hazard prevention and control systems for specific laboratory processes must be readily shared between lab workers, their colleagues, and lab supervisors. In order for these control systems to be effective in a transferable and sustainable way, effective risk management communication tools must be present. These tools need to be adaptable and sustainable as research processes change in response to evolving scientific needs in discovery based laboratories.

In this manuscript, the application of a risk management tool developed in the oil and gas industry known as a "bowtie diagram" is assessed for application in the laboratory setting. The challenges of identifying laboratory hazards and managing associated risks as well as early experiences in adapting bowtie diagrams to the laboratory setting are described. Background information about the bowtie approach is provided and the technique illustrated using an academic laboratory research scenario. We also outline the role bowtie diagrams could play in a proactive safety culture program by facilitating hazard communication and maintaining hazard awareness across a wide spectrum of stakeholders.

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INTRODUCTION

A series of highly publicized incidents have highlighted the physical hazards of energetic, pyrophoric, and flammable materials used in academic research laboratories.[1–3] These incidents have brought attention to the challenge of safely managing the multiple, rapidly-evolving chemical processes that are characteristic of the laboratory environment. To keep pace with this evolution, the Association of Public and Land Grant Universities (APLU) has suggested that a new approach to laboratory safety is required. The APLU suggests that the new approach should address both technical and cultural aspects of this issue.[4] Several hazard identification, evaluation, and management tools have been described in the National Academy's *Prudent Practices in the Laboratory* and the American Chemical Society's publication *Identifying and Evaluating Hazards in Research Laboratories* to address the technical side, but the cultural aspect of the challenge requires that risk management knowledge must be readily shared between laboratory workers, their colleagues, and administrators.[5,6] To be effective, risk assessment and communication tools must also be adaptable to research processes as they change in response to evolving scientific needs.

SAFETY MANAGEMENT IN THE LABORATORY SETTING

Academic laboratories host many different operations serving a variety of purposes. Teaching, research and service laboratory functions are routinely intermixed with personnel moving between them as needs arise. This diversity in laboratory operations is a significant challenge when addressing safety management in this setting.

Academic laboratories are quite diverse in scope and activities. For the purposes of this paper, "laboratories" refer to workplaces that conform to the

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Occupational Safety and Health Administration's (OSHA's) definition of laboratory "scale and use" defined in 29 CRF 1910.1450.[7] In these laboratories, diverse chemicals are used in multiple processes in quantities that one person can safely manipulate using traditional laboratory safety practices. These practices include generic engineering controls such as laboratory ventilation and chemical storage devices, emergency response equipment, worker training and oversight, and personal protective equipment. It is important to remember that many research activities in higher education go beyond this definition by involving significant non-chemical hazards, using amounts of chemicals beyond OSHA's definition of laboratory scale, or by using materials for which insufficient hazard information is available.

As noted by both the US Chemical Safety Board (CSB) and the National Research Council (NRC), the traditional laboratory safety model is being challenged in the modern academic laboratory.[1,8] Emerging factors, such as the increasing turnover and diversity of laboratory workers, and the creation of new materials with unknown hazards, have rendered the traditional laboratory safety practices listed above inadequate, taken alone, for addressing research hazards. Preventing and mitigating laboratory incidents requires effective management of a system of barriers that includes physical, operational, and organizational elements. For example:

- The institution must determine what facilities and management resources are required to support specific research proposals (including the ability to house new chemicals and assess additional hazards they create in the laboratory) and determine whether such facilities are available when such proposals are funded;
- Laboratory equipment with appropriate controls must be provided for the experiments being conducted;
- Safety equipment must be identified, provided, maintained, and inspected to ensure that it will function as designed if it is needed (i.e. emergency shut-offs, safety showers, eye washes, etc.);
- Organizations and individual laboratories must support safety education and training by establishing clear safety expectations through policies and procedures and then maintaining oversight services that identify opportunities for improving training;
- Appropriate emergency response and waste management services must be provided for the laboratory work being conducted, and
- Continuous monitoring and response is required at all levels of an organization to ensure adequate and effective barriers to prevent or mitigate laboratory incidents.

Compounding the challenge of effective safety management is the increasingly interdisciplinary nature of laboratory science. As biologists, physicists and engineers collaborate with chemists, the complexity of the hazards presented increases correspondingly. Control strategies for chemical hazards, biological agents and physical dangers can differ significantly and sometimes compete for attention and resources. Cross-disciplinary collaboration can result in workers being involved in laboratory processes that they may not be well educated in. For this reason, it is important to develop a safety communication system that clearly highlights significant hazards while being easy to use, share, and modify as work changes.

It is also important to remember that the management of laboratory safety has the potential to affect people other than those physically conducting the work. The disruption of neighboring activities on many campuses and the legal impacts of the 2008 fatal fire at the University of California, Los Angeles (UCLA) made it clear that laboratory incidents can have consequences impacting not just the principle investigators overseeing the work, but neighboring researchers and institutions as a whole in terms of both productivity and reputation.[9,10] Even incidents that result in no injuries can have serious financial consequences, such as recovery costs of over $1,000,000.[11]

These considerations mean that a larger network of stakeholders should be included in developing safety tools. The bowtie approach described in this paper presents an opportunity to improve institutional understanding of laboratory risks by facilitating communication and management of these issues among the wide variety of stakeholders in academic laboratory research. Stakeholders include university presidents, senior administrators, laboratory faculty and staff, environmental health and safety staff, and students.[4] Such a diverse group of stakeholders means that communication tools may have to be redesigned with different levels of detail to address various questions from different groups. Fortunately, software for building bowties is available to support the reuse of information developed for one set of stakeholders, thus communication tools may easily be adapted for the needs of others.[12,13]

To address this daunting list of needs, ongoing communication among the various stakeholders at an academic institution is necessary. A graphical representation of an institution's safety barriers and controls is likely to be significantly more valuable to support communication than a collection of text-based policies, procedures, and checklists – especially when communicating with audiences who do not have a background in the chemical sciences or risk assessment.

THE ORIGIN OF BOWTIE DIAGRAMS

Using graphical imagery to describe safety systems has been shown to be effective in supporting hazard communication needs. In 2000 James Reason presented a popular model depicting the progression of an incident through a series of leaky barriers.[14] This model, aptly referred to as the "Swiss cheese model", is presented schematically in Figure 1. In this model the slices of cheese represent "barriers" such as those outlined above, while the holes represent barrier deficiencies in specific elements in the system. These deficiencies can allow a threat to penetrate the system and result in an incident. An increased number of barriers with smaller and fewer holes will lead to a more robust barrier system for preventing incidents.

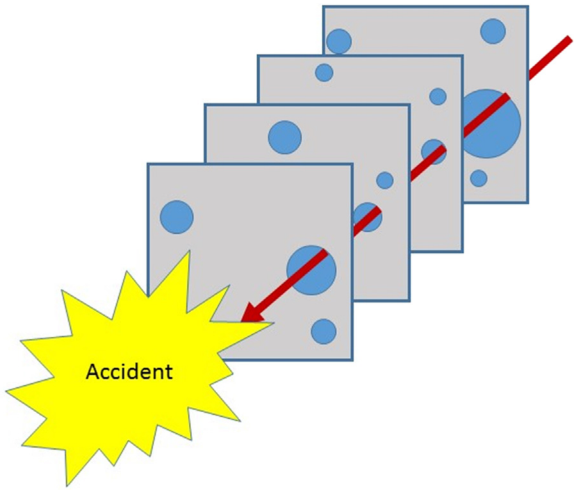

Figure 1. James Reason's Swiss Cheese model of accident causation.

A more sophisticated graphical tool known as the "Bowtie Diagram" also exists. Bowties garner their name from their shape (see Figure 2) and depict the relationships between hazards and barriers in a holistic way. The first appearance of bowtie diagrams has been attributed to lectures on Hazard Analysis given at The University of Queensland, Australia in 1979, but the exact origin of bowtie diagrams is not clear.[15] Their use was pioneered largely by the oil and gas industry, and now can also be found in the aviation, mining, maritime, chemical and health care industries.

After hazards have been identified, the bowtie tool can be used as a risk assessment aid and communication device to depict the number and type of barriers (e.g., physical, organizational, or operational) that must fail in order for an incident to occur. While this model has been used in large-scale industrial settings, we believe the concept can be adapted to the laboratory setting to create a useful communication tool for this challenging management environment.

Because best practices in developing bowtie diagrams are still evolving, there are a variety of terms and concepts that need to be defined in order to develop a useful bowtie diagram. The precise use of these terms and concepts will vary depending on the expertise of the people involved in developing the diagram. However, the main goal for developing a bowtie diagram is to aid in communication and assessment of the fundamentals of the safety system. The following section describes the basic process of developing a bowtie.

- <u>Hazard</u> – As illustrated in Figure 2, at the top of a bowtie diagram is a hazard of concern, i.e. something that has a potential to cause damage or loss if it is not properly controlled. Hazards are dangerous intrinsic properties of the materials or process that cannot be eliminated. In a laboratory setting, these hazards could be described as "explosive solid," "flammable liquid," or "corrosive chemical" amongst others. Safety Data Sheets that conform to the Globally Harmonized System provide a general approach for identifying chemical hazards associated with a process.
- <u>Top Event</u> – The center of the bowtie is the 'Top Event' which identifies the point in time when control of a specific hazard is lost, and this loss could result in specific forms of harm.
- <u>Threat</u>– The threats listed on the left side of the bowtie are events that can begin the chain of action leading toward the top event.
- <u>Control</u>– Preventive barriers, shown between a threat and the top event, are designed to either prevent the

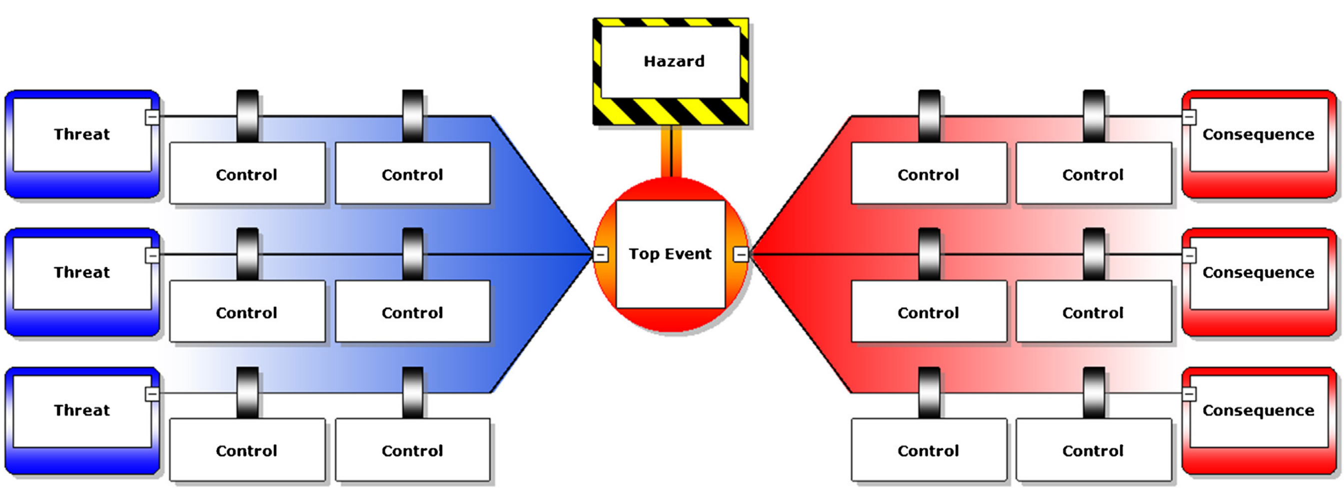

Figure 2. Generic bowtie diagram depicting multiple threats that can escalate to a loss of control of a hazard, and in turn, progress to a variety of negative consequences.

threat from occurring or stop the escalation of a threat to the point where it becomes involved in a top event. If a top event occurs, then the mitigation barriers on the right side of the bow tie are intended to either stop or minimize the severity of unwanted consequences.

A LABORATORY EXAMPLE

In March 2016, the Division of Chemical Health & Safety (DCHAS) presented an interactive symposium at the American Chemical Society (ACS) national meeting. The symposium was held to assess the value of the bowtie methodology in a laboratory setting.[16] The example used in the activity was based on the 2011 CSB case study of a laboratory incident at Texas Tech University (TTU).[1]

To construct the bowtie, participants were asked to identify its parts in accordance with widely accepted best practice in the oil and gas industry in the following order[17,18]:

1. Hazard/Top Event
2. All Consequences
3. All Threats
4. Preventive Barriers
5. Mitigation Barriers

Initially a variety of possible top events were identified, but the hazard was generally agreed upon by all participants as "energetic material" Possibilities for the top event discussed were:

- Intentional scale-up
- Explosion/detonation
- Exceed safety critical limit (In this case, a safety critical limit is the minimum amount of material that could cause permanent bodily injury if detonated)

The group agreed to use "exceed safety critical limit" as the top event for two reasons. First, identifying the scale-up as "intentional" limits the applicability of the bowtie. For example, prior to the 2011 incident, another TTU student unintentionally scaled-up the synthesis of another energetic material.[1] While the barriers to prevent unintentional or intentional scale-ups may be different, once safety critical amounts are exceeded, the barriers to prevent or mitigate consequences of a detonation are the same. Therefore, choosing "exceed safety critical limit" allows the bowtie to cover multiple threat scenarios for a single hazard.

Secondly, choosing "exceed safety critical limit" as opposed to "explosion/detonation" puts the risk management focus on a point in time when the laboratory workers can still respond and avoid a detonation altogether. Figure 3 presents the initial bowtie diagram with the group-decided hazard and top event.

Several potential consequences were suggested:

- Injury/fatality due to detonation
- Property damage due to detonation
- Reputation damage due to detonation
- Loss of business/productivity/grant funding due to detonation
- Regulatory/external review

Potential consequences extend beyond the individuals and laboratory involved and can affect multiple departments in the university, as apparent from the above list. Although property damage and regulatory/external review would be valid consequences, due to the time constraints the workshop leaders focused on three consequences listed in the evolving bowtie diagram shown in Figure 4.

Identifying potential threats was the most challenging part of constructing a bowtie for the group. The participants initially listed the following as potential threats that could lead to exceeding safety critical limits (top event):

- No written procedures
- No personal protective equipment (PPE) policy
- Untrained laboratory workers
- Inadequate supervision
- Lack of communication

Listing failed or degraded barriers (such as those listed in the bullets above) as threats is a common mistake in bowtie development. In response, the workshop leaders guided the group toward threats describing an initiating event that if left unchecked could escalate to a laboratory worker exceeding a safety critical amount of energetic compound. After this instruction, the group identified three key threats:

- Intentional synthesis scale-up of energetic material
- Inadvertent synthesis scale-up
- Unauthorized (criminal) activities

Figure 5 shows the developing bowtie diagram which now includes the group-identified threats that could lead to the top event (exceeding the safety critical limit). Finally, the group discussed and listed the various preventive and mitigative barriers. The resulting bowtie diagram based on this workshop activity is shown in Figure 6. The bowtie diagrams in this manuscript were prepared using BowTieXP software.[13]

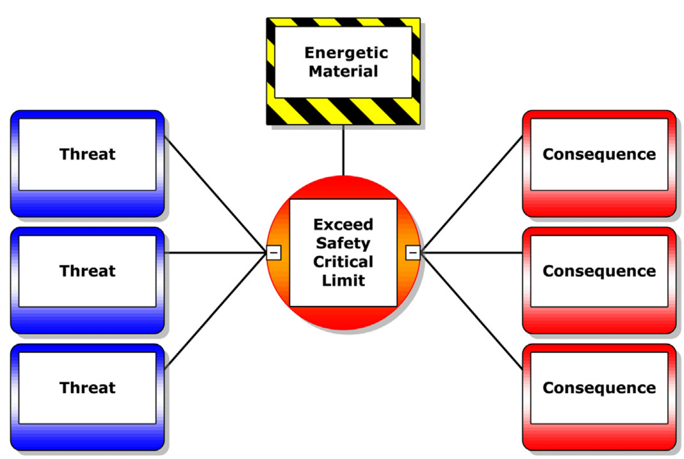

Figure 3. Initial bowtie diagram showing hazard and top event.

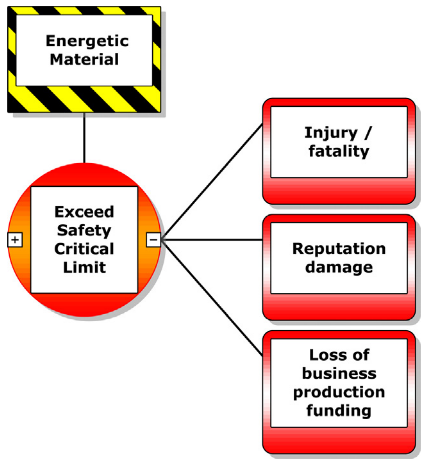

Figure 4. The evolving bowtie diagram showing group suggested consequences.

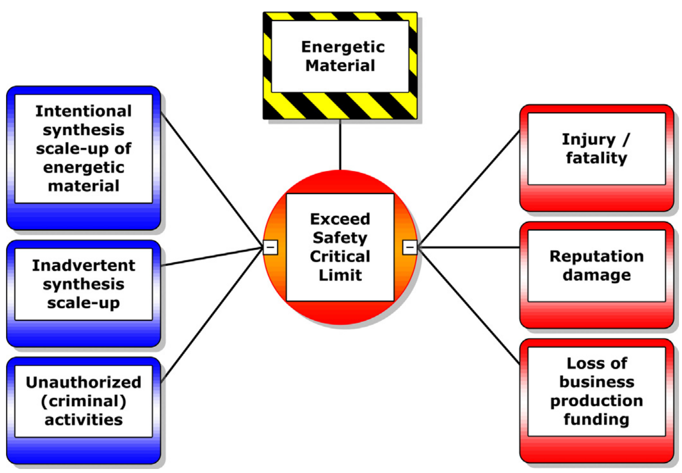

Figure 5. Bowtie diagram showing the threats agreed upon after group leader guidance.

BOWTIE DEVELOPMENT PRECAUTIONS

A potential pitfall of the bowtie approach is that users over-identify barriers and generate a false sense of safety since more barriers may be expected to reduce associated risks. For example, the bowtie in Figure 6 lists "activating emergency alarms and response" as a barrier. To ensure this barrier functions, a laboratory worker needs training to know where the alarm is located, how to activate it, and how to respond once it is activated. Furthermore, it is imperative the alarm is properly maintained so that it will function when activated. Ultimately, the alarm and associated training and maintenance actually represent a single barrier system, without which there is no assurance the barrier will function at all. When an "alarm" is listed as a barrier, it should be with the understanding that there is safety management system supporting it that includes training and maintenance. Without this, there are "holes" in the barrier analogous to the Swiss cheese model.[14]

Management systems are the formal processes where management (e.g., principal investigator, department chair, etc.) commits to policies or procedures that support safety, implements the policies and procedures, monitors their performance, and implements appropriate corrective actions when necessary.[19] Monitoring performance and implementing corrective actions should be a continual process which results in improving the management of risks and safety throughout the lifetime of a research program. This is true whether the barrier is physical in nature like the alarm example (technical), or an organizational policy (cultural). ***Ultimately, a piece of paper is not a barrier – risk assessment and management is an active process.*** It is the actual work conducted under the policy or procedure that creates the barrier. If a policy or procedure is not consistently monitored and reinforced, the operational

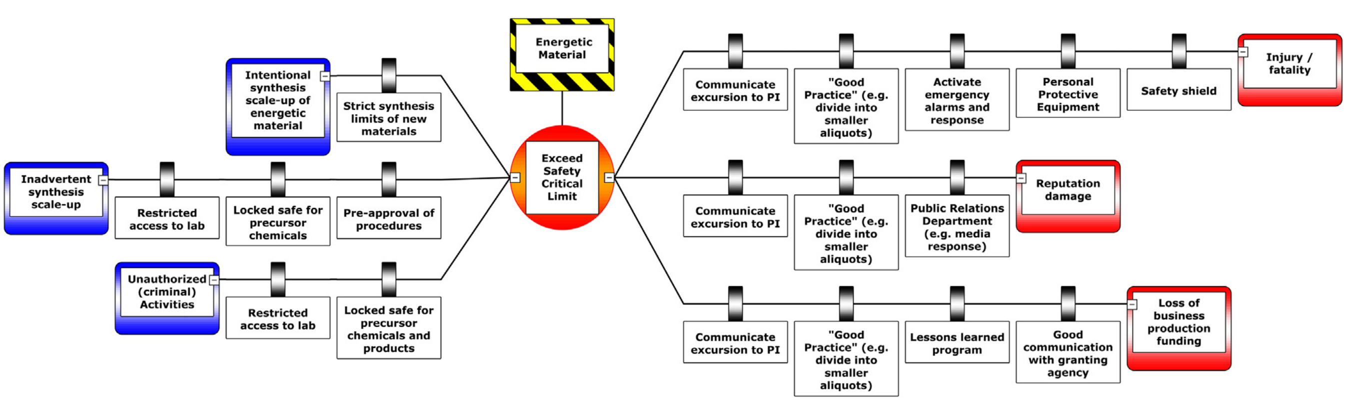

Figure 6. Bowtie diagram for the detonation of energetic material in a laboratory setting.

barrier can degrade and fail. In the laboratory setting, operational barriers are necessary and heavily relied upon. This is illustrated on the bowtie in Figure 6 where the only barrier listed to prevent "intentional scale-up" is a policy not to synthesize amounts greater than the safety critical limit.

USING BOWTIES TO FACILITATE RISK CONVERSATIONS

Bowties are part art and part science. There is no single "right" way to create a bowtie. As long as a group developing the bowtie leverages in-house expertise and identifies their most significant hazards and the needed controls, then the bowtie can be a useful tool to facilitate risk conversations amongst numerous stakeholders. For example:

- As the bowtie in Figure 6 indicates, mitigating potential consequences may require resources outside of the chemistry department such a public relations department to handle media attention.
- Bowties help depict whether a risk management approach is focused on preventing dangerous situations or mitigating them after they have occurred. For example a fire hazard will not be controlled by PPE and so a well-developed bowtie would highlight that PPE is only helpful in mitigating potential burn injuries, not in preventing the hazardous conditions that can lead to a fire from occurring in the first place.
- A graduate student or other laboratory worker initiating a procedure can review an existing bowtie as a reminder of the critical barriers to ensure they are in place and functioning before initiating work.
- During a laboratory safety audit, an inspector without expert knowledge on a process and its hazards could review a bowtie and ask about the safety management systems connected to the barriers indicated on the diagram. This can include talking with the individuals responsible for monitoring and maintaining different barriers.
- Incidents and serious consequences occur when barriers fail. Bowties can be the starting point of an accident investigation to determine how and why the barriers had failed, were inadequate, or were bypassed.

CONCLUSION

Bowtie methodology could prove useful in aiding universities to further improve how they manage their laboratory risks. It provides a structured approach to identifying key safety barriers and controls so their strengths and conditions can be monitored more effectively to prevent barrier degradation. These are the types of improvements necessary to go beyond current laboratory safety practices and achieve a proactive safety culture.

Bowties facilitate effective risk conversations by providing a visual aid to prompt conversation rather than relying on sometimes cumbersome text-based policies, procedures and checklists. Presenting information in multiple formats supports learning by a diverse group of workers whose learning styles, languages skills and technical expertise can be expected to vary significantly. Universities can also apply this technique as part of their auditing process to help identify where barriers may need to be strengthened or added, and this can drive the creation of effective actions toward further risk reduction efforts. Ultimately, bowties provide a good roadmap for assessing the quality and number of risk controls to prevent serious laboratory incidents and facilitate the identification of clear actions to improve controls and advance the "cultural" side of safety management.

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