Using Incident Reporting to Integrate Hazard Analysis and Risk Assessment into the Unit Operations Lab

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Abstract

Since 2017, instructors from six universities have collaborated to better understand and improve the integration of process safety into chemical engineering unit operations (UO) laboratories. While past studies by the team have focused on assessing the state of UO lab safety education, the current study aims to implement new strategies for improving process safety education in the UO labs. By examining the Safety and Chemical Engineering (SAChE) process safety learning outcomes, hazard analysis and risk assessment were identified as the first priority for integration into these university labs, as they are most relevant to a laboratory setting and not heavily covered elsewhere in these university chemical engineering curricula. For integration, a safety incident reporting structure was developed to allow students to report safety incidents and assess hazards and risk levels. Students were asked to categorize the incidents as being related to personal, process, or environmental safety, and were then asked to assess risk levels. The goals of the reporting structure were to increase student awareness of these topics, improve safety culture, and develop an understanding of actual risk frequencies in the undergraduate teaching labs.

After development, four of the six universities were able to implement the reporting structure in their UO labs, although specific data could only be reported from three due to timing of IRB approval. Risk and frequencies were determined by analyzing over 400 incidents or near-misses from these three universities, showing that 62% of safety incidents were related to personal safety, whereas 18% were process-related and 20% were environment-related. Of those incidents, 45% were characterized as near-miss incidents where students were able to prevent the hazard from escalating to a level requiring intervention. Prior to implementing this system, very little or no documentation on safety incidents was kept; often, only incidents requiring medical attention were reported to the instructor and/or lab manager.

Pre- and post-tests were also utilized to understand the impact of the incident reporting on process safety-related learning outcomes. From the pre-test data (approximately 200 total students) at the start of the semester, students had a stronger understanding of personal safety than they did process or environmental safety. When comparing pre- and post-survey data, self-reported knowledge levels were significantly improved for understanding of consequence, frequency, process safety and environmental safety. Interestingly, improvements in self-reported understanding and knowledge gains were stronger for those students who had never completed an industrial internship. To date, all instructors have observed that the incident reporting structure has resulted in a positive change to the safety culture of the laboratories. These results alone show the positive effect of integrating incident reporting into the UO laboratories.

Background and Motivation

Over the past few years, a group of instructors from six universities has been collaborating to better understand how process safety concepts can be integrated into the chemical engineering unit operations (UO) laboratory. Past work has detailed available process safety resources relevant to the UO lab [1], as well as an assessment of how well the six institutions teach the Safety and Chemical Engineering (SAChE) process safety learning outcomes [2] as part of UO and the entire curriculum [3]. The former work identified a lack of UO-specific active learning activities that could be easily integrated into a course, and the latter identified that risk assessment and hazard identification were not only highly relevant to UO courses but were inadequately covered or not taught at all at the six institutions. Furthermore, the authors could find no data that quantified the frequency of incidents, near-misses, or positive observations within a UO laboratory course. This kind of data is commonly collected in industrial settings to help benchmark frequencies, create risk matrices, and identify areas for improvement [4]. The current work aims to address all of these shortcomings via the development and implementation of an incident reporting structure that focuses on hazard identification and risk assessment.

The project has several overarching goals:

1. To teach students about risk assessment
2. To have students practice hazard identification and reporting of good safety practices, near misses, and incidents
3. To quantitatively benchmark the hazards and frequencies of events in the lab courses so targeted improvements can be made in the courses' overall safety
4. To improve safety culture in the lab

To assess risk and teach students about risk assessment, a semi-quantitative risk matrix may be used [5]. The risk matrix consists of consequences and frequencies (probability of incident occurring) (Figure 1). Both of these variables need to be defined and quantified in order for the risk to be assessed. Consequences can be categorized into different types based on who or what is affected, such as personal, process, or environmental. Personal consequences are defined as harm to individuals, process consequences focus on the equipment and the chemical process system, and environmental consequences focus on the effect to the surroundings of the chemical process system. Each type of consequence should be rated for severity by using a numerical scale with definitions for each number on the scale. Levels of severity may include a near-miss (nothing happened, but there was a potential for harm) at the lower level up to a catastrophic event (death or irreversible damage) at the higher level. The quantitative values assigned to these severity levels may, for example, range from 0-4, with 0 assigned to a near-miss and 4 assigned to irreversible damage (Figure 1). The frequency component of the risk matrix assigns a numerical value based on the probability of a consequence occurring. For example, a consequence that is very unlikely to occur because current control measures are effective may be assigned a value of 1, while a consequence that is likely to occur due to inadequate or nonexistent control measures may be assigned a value of 4 (Figure 1). Multiplying the value for the consequence and the frequency results in the "Risk Product" that can be used to analyze the level of risk.

To teach UO laboratory students about the frequency component of the risk matrix, an incident reporting system was designed and implemented. An example of the system can be viewed at the link provided at the end of this paper. This system was based on reporting systems used in industry, which serve several purposes [7,8], including (1) quantifying the number of new occurrences to identify potential incidents, (2) quantifying the number of repeating occurrences to enable the company to address the most frequent and highest risk incidents, and (3) maintaining awareness of safety and developing a safety culture [9]. Utilizing the incident reporting system enables the university UO lab instructors to collect data similar to that collected for industrial purposes (which could be used to benchmark future course safety), while also helping the students understand how frequency data is acquired.

In order to assess student learning, pre-semester and post-semester surveys were used to measure changes in awareness and knowledge level of risk, consequence, frequency, and differences between personal, process, and environmental safety.

Consequence for incident					Probability of incident			
					Control measures are effective	Multiple control measures exist, but effectiveness is not guaranteed	At least one control measure exists, but effectiveness is not guaranteed	Control measures are nonexistent or inadequate
					Very unlikely	Improbable	Occasional	Likely
Personal	Process	Environment			1	2	3	4
Fatalities or incapacitation	Equipment completely destroyed	Extreme and irreversible change	Catastrophic	4	4	8	12	16
Permanent disability, but not incapacitation	Contractor must repair equipment	Significant and unacceptable alterations requiring contractor to mediate	Very serious	3	3	6	9	12
Lost or restricted work days	Instructor can repair equipment	Measurable changes requiring campus personnel to mediate	Serious	2	2	4	6	8
Medical treatment or first aid required (must be recorded)	Student can repair equipment	Minor effect (likely not measurable)	Minor	1	1	2	3	4
Potential for injury or no first aid needed	Potential for repair or no repair needed	Potential for environmental effect or no effect	Near miss	0	0	0	0	0

Risk Product	Description
16	Unacceptable level of risk; work should not be started until mitigation steps are identified and implemented
12	Requires more layers of protection; need supervisor support
8-9	More layers of protection are recommended; need supervisor support
4- 6	Current layers seem adequate; confirm with supervisor
0-3	Layers of protection are adequate; work can be started

Figure 1. Risk matrix for university UO laboratories [6]

Methods

Study participants were engineering students enrolled in UO at four medium-to-large R1 universities: University of Kentucky (89 enrolled), University of Michigan (64 enrolled), University of Minnesota (109 enrolled), and Washington University in St. Louis (42 enrolled). While implementation structure was maintained across programs as much as possible, slight modifications were made at each university to obtain Institutional Review Board (IRB) approval. All four universities implemented the incident reporting structure in their courses, although due to the timing of IRB approval, incident reporting data from the University of Kentucky could not be reported in this study.

Prior to the start of incident reporting and after the conclusion of the semester, students were asked to complete pre- and post-surveys to assess understanding of key process safety related concepts and learning gains. IRB approval for this data was obtained for all four universities and is presented here. Participation in the pre- and post-tests was voluntary and anonymous. At the start of the survey, students were shown an IRB-approved cover letter and asked to consent to participation in the study. To control for process safety related knowledge due to prior internship and research experience, students were first asked to identify if they participated in a single internship, multiple internships, or lab research experience. If participation was identified, they were asked to describe how safety was integrated into that experience. Students were then asked to rate their understanding of the following concepts: risk assessment, consequence, frequency, personal safety, process safety, and environmental safety. Understanding was ranked using the following categories: “I don’t know what this term means” (0), “Not well at all” (1), “Slightly well” (2), “Moderately well” (3), “Very well” (4), or “Extremely well” (5). For the post-survey, an additional question was added where students were asked to rate the extent to which they made gains as a result of the UO course for the following concepts: risk assessment, consequence, frequency, personal safety, process safety, and environmental safety. Gains were categorized using the following categories: “None at all” (0), “A little, (1), “A moderate amount” (2), “A lot” (3) or “A great deal” (4). Because pre- and post-data were anonymous, data were aggregated to assess significance. Subgroups of students who had completed internships versus those who had not were analyzed to investigate differential effects on students with and without industrial experience. Likert-scale distributions were analyzed to identify significant differences between different populations using the Mann-Whitney U test with a significance level of 0.05.

Incident reporting was included as part of a grade for the UO course at each institution, with students submitting their team number or experiment to receive credit. At the start of the incident report, students had the option to consent for use of their incident reporting data in the research study. Due to the timing of IRB approval, data from incident reports at the University of Kentucky were not included in this part of the research study. Students were first given definitions of personal, process, and environmental incidents or near misses and the definition of a “positive observation,” which was defined as an event that has the potential to decrease the occurrence of a personal, process, or environmental incident. Students were then asked to categorize their incident, near miss, or positive observation based on these definitions. For each incident type, they were brought to a series of questions asking them to further describe the incident. They were first asked to describe the incident or near miss and categorize the event based on common categories identified within that incident type. For instance, categories for an environmental incident include liquid spill, liquid spray, vapor release, unlabeled or mislabeled container, unwashed glassware, lack of secondary containment, and messy lab bench or work area. Students were then asked to identify the consequence of the incident with incident levels defined as appropriate for each incident category. For instance, personal incident consequence levels were described as: (0) Near miss—incident with no medical treatment needed or incident with potential for injury; (1) Minor—medical treatment or first aid cases; (2) Serious—lost or restricted work days; (3) Very serious—permanent disability, but not incapacitating; and (4) Catastrophic—fatalities or incapacitating cases. They were then asked to describe any action that was taken in response to the incident. Finally, students were asked to assess the consequence level had the incident escalated to its worst-case scenario and describe the rationale for the choice of consequence level. For this ranking, consequence level options remained the same as the actual consequence level options, but the option for a near-miss incident was removed. In addition to submitting incidents, students had the option to submit positive safety observations. For a positive observation, students were asked to identify the category of the observation (personal, process or environmental), describe the observation and describe action that was taken in response to the observation. For analysis, data from incident reports were aggregated within the university, as well as across universities.

Results & Discussion

Incident Reporting

The incident reporting structure allowed students to select between one of four incident types: personal safety incident, process safety incident, environmental safety incident, or positive observation. Although some variation from school to school existed, students seemed to focus largely on personal safety incidents as well as positive observations, while process and environmental incidents were less commonly reported (Table 1). This trend could potentially be a result of the students' greater awareness of personal safety through previous lab courses and experiences. Alternatively, the trend could be due to UO experiments being less prone to equipment and environmental safety issues compared to personal safety issues.

Table 1. Number of incidents reported for each type of incident at each participating university as well as overall.

Incident or Near-Miss Type	Number of incidents			
	University of Michigan	University of Minnesota	Washington University in St. Louis	Overall
Personal	47	132	70	249
Process	14	34	25	73
Environmental	16	29	36	81
Positive Observation	72	94	10	176
Total Reported	149	289	141	579

Within each incident type, students identified the category of the incident from among common issues. Figures 2-4 show the frequency of each category at each school and overall. For personal incidents (Figure 2), over half of the total personal incidents reported were due to the top three categories: (1) Slips, trips, and falls; (2) Not wearing PPE; and (3) Chemical splash (skin). For process incidents (Figure 3), leaks were the predominant category (nearly 25% of all reported process-related incidents), while broken sensors, loose pieces, and cracks were also quite common. For environmental incidents (Figure 4), liquid spills dominated the reporting, making up 50% of the incidents. Messy lab benches and lack of secondary containment were also relatively common. The top categories at each school were somewhat consistent, although each school had variations in which categories were most common within each type of report.

For all incident types, the "Other" category was commonly selected (12-35% of total responses). Descriptions of the incidents in this category varied widely, and sometimes included what the authors might consider "mis-categorized" incidents. For example, students at one school listed "unlabeled containers" as a process incident, even though that is one of the primary environmental categories. Similarly, "burn" was listed under "Personal—Other" even though both chemical and heat burns could have been selected. The "Other" category also highlighted common incidents that were not one of the original categories, such as chemical spill (solid), broken glass, mishandled chemical waste, broken valve, or ingestion of chemicals. Future iterations of the reporting survey could include these categories.

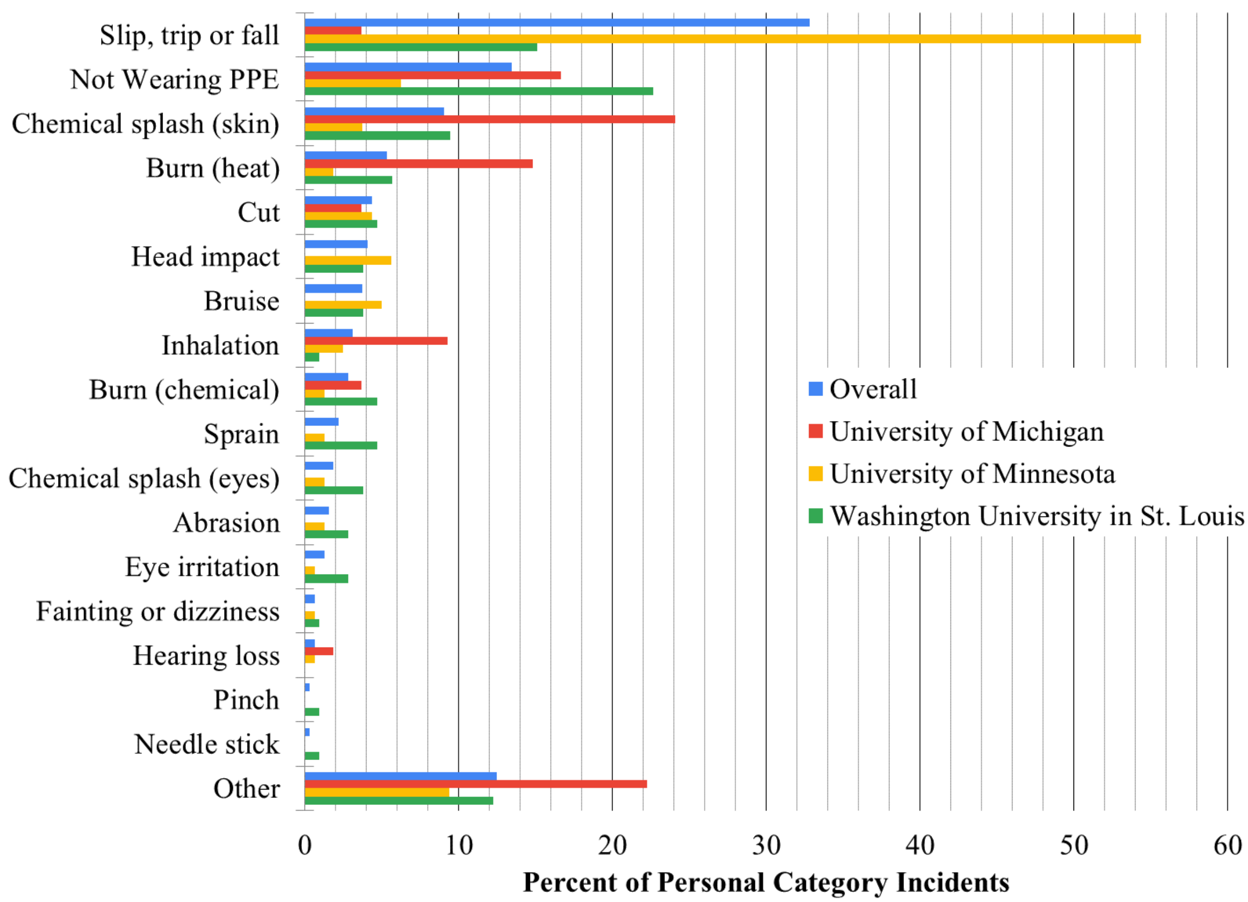

Figure 2. Frequency of categories within the personal incident type of reporting.

Some categories, perhaps to the authors' surprise, were not commonly reported. For example, unlabeled containers and unwashed glassware made up less than 5% of all environmental incidents reported, although the authors expected these to be common issues in the lab due to previous experience in the laboratory. Fortunately, chemical splashes to the eyes, fainting/dizziness, pinches, and needlesticks were very uncommon, as were missing pieces, software bugs, scratches, and discoloration of equipment. Anecdotally, most of the instructors using the incident reporting activity noticed improvements in lab safety culture, indicating that perhaps this activity had helped achieve one of the authors' goals.

Following categorization of the incident being reported, students were asked to assess not only the actual consequence level (on a rating from 0: Near Miss to 4: Catastrophic) but the potential consequence level (from 1: Minor to 4: Catastrophic). Figures 5-7 show the overall frequency of these assessment levels, broken down by type of incident (personal, process, environment). For the three types, between 77% and 99% of incidents' actual consequence level were rated either a 0 (Near Miss) or 1 (Minor). Particularly (and fortunately) for personal incidents, Near Misses comprised nearly 90% of reports.

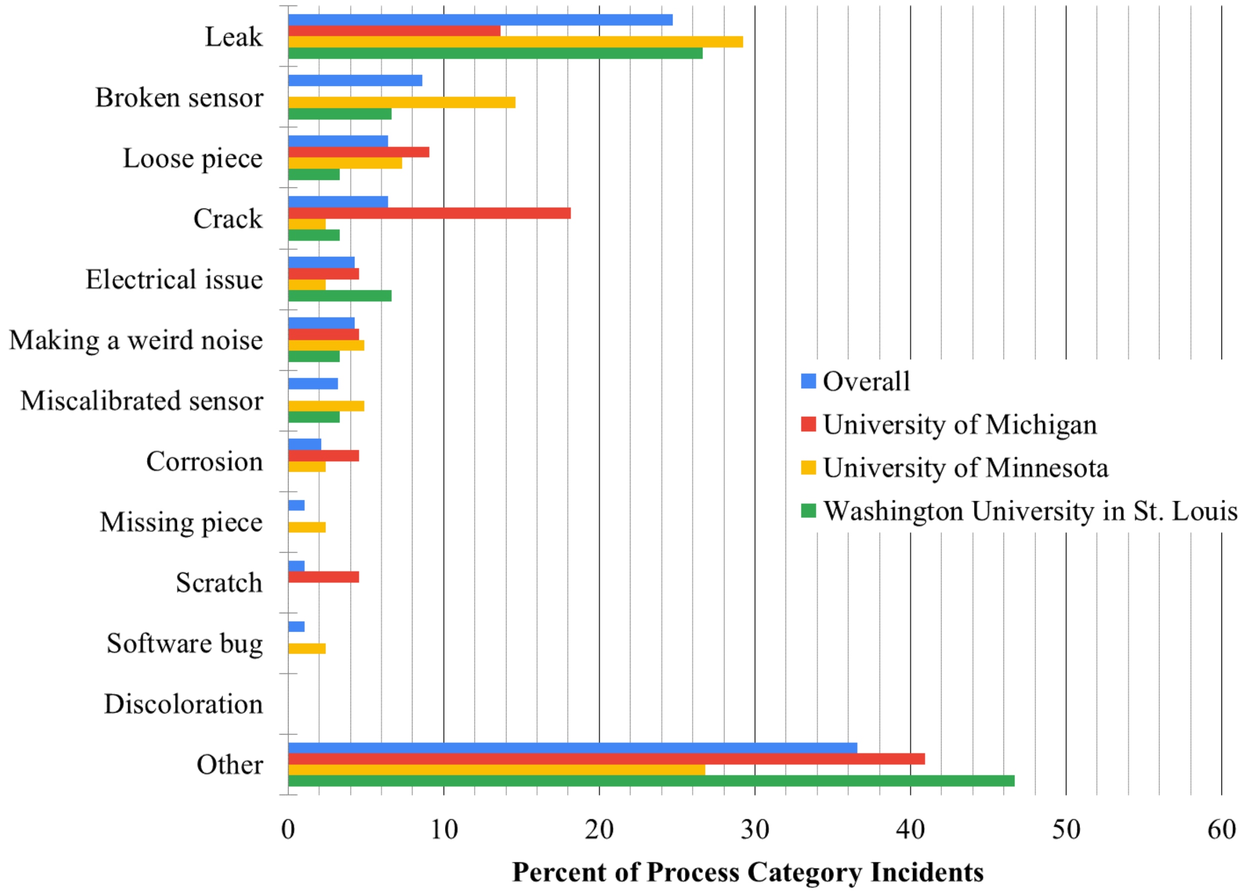

Figure 3. Frequency of categories within the process incident type of reporting.

Notably, some of the actual consequences were listed as more severe. One Level 4 personal incident ("Catastrophic: Fatalities or incapacitating cases") was reported, but the incident was described as a trip and fall (not requiring any medical attention) and, therefore, was miscategorized. Four personal incidents were listed as Level 2 (Serious); these included minor heat and chemical burns that may have taken several days to heal. More worrisome is that for at least one of these events, the instructor was not notified, even though students were clearly directed to inform the instructor of any injury. This type of issue highlights a weakness in lab safety instruction, and this particular issue will be addressed more strongly in future iterations of the course. A positive result from the data is that no legitimate Level 3 or 4 personal-type incidents occurred.

For both process-type and environmental-type incidents, higher actual consequence levels were more common. For example, in the case of a small spill of caustic solution, discoloration of the flooring occurred, so students correctly listed the environmental incident as "Very Serious: Significant and unacceptable alterations to environment requiring contractor to mediate".

Notably, several "Catastrophic" process incidents were reported, although most of these were referring to broken glassware. This particular case highlights an issue with how the authors

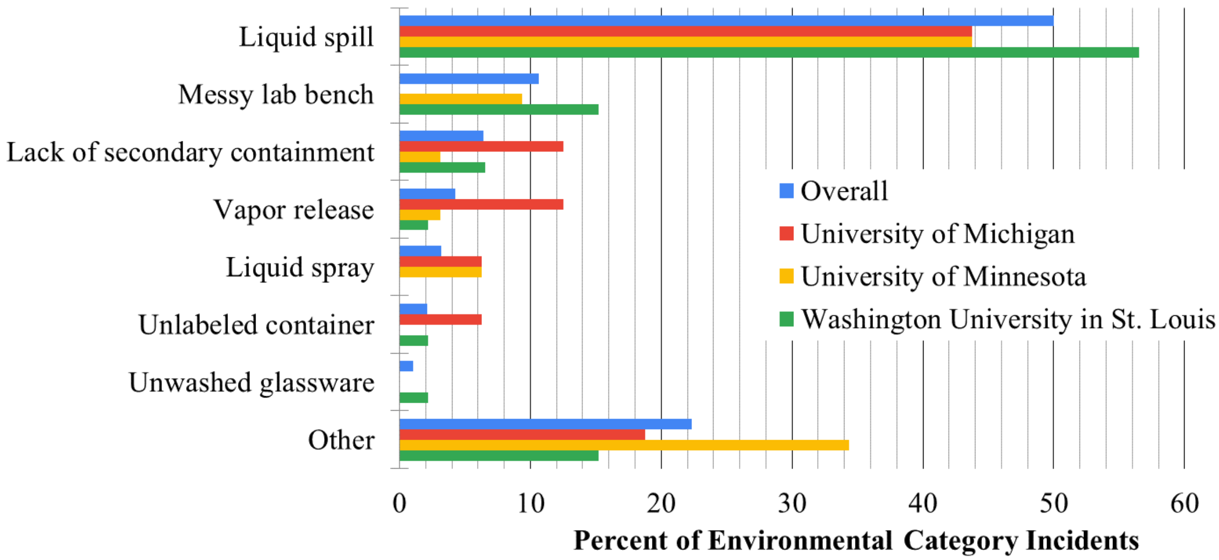

Figure 4. Frequency of categories within the environmental incident type of reporting.

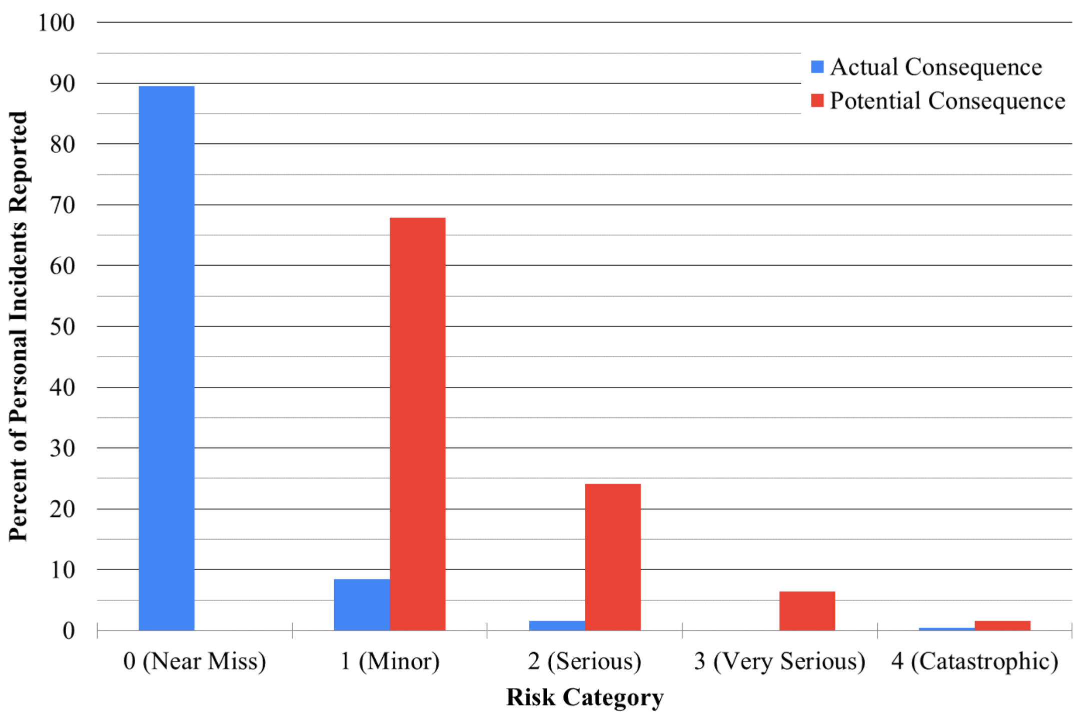

Figure 5. Overall frequency of student assessment of actual and potential consequence levels for the personal-type incidents reported.

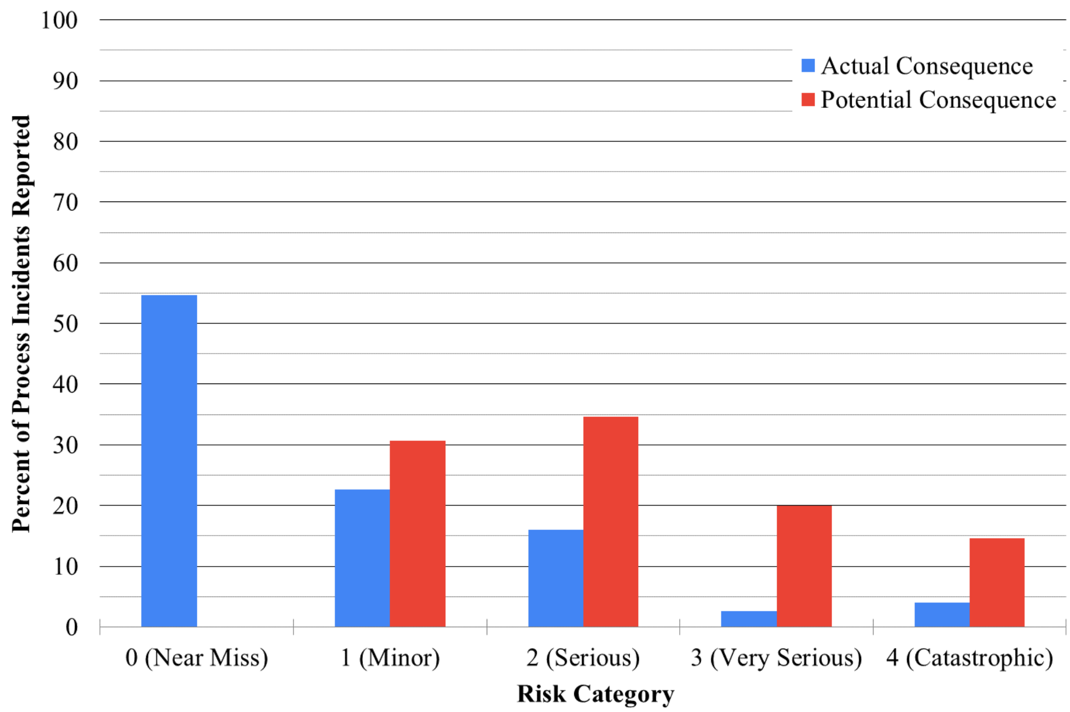

Figure 6. Overall frequency of student assessment of actual and potential consequence levels for the process-type incidents reported.

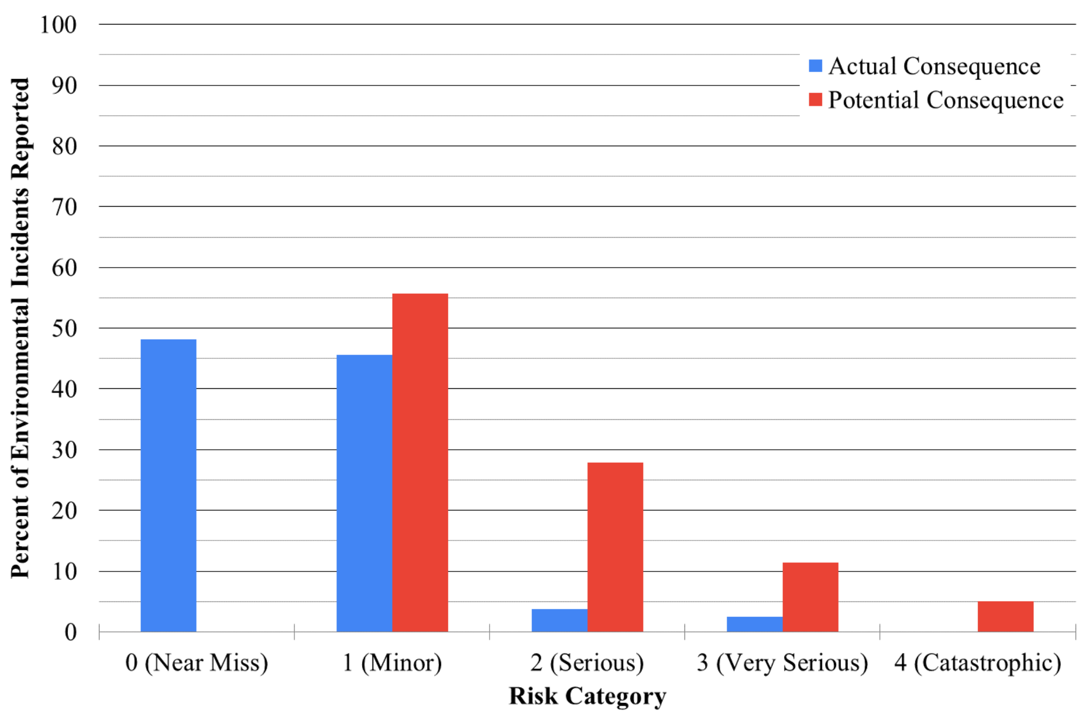

Figure 7. Overall frequency of student assessment of actual and potential consequence levels for the environmental-type incidents reported.

defined the level: “Equipment completely destroyed”. When writing the consequence definitions, the authors had envisioned that the incident report would refer primarily to the unit operation equipment (e.g., distillation column, dryer, or pump), not to what one might consider basic laboratory supplies. Therefore, although the student categorization of broken glassware as “Catastrophic” is technically accurate for one minor piece of experimental equipment, it was not reflective of a true catastrophic incident for the experimental process. These consequence definitions will likely be revised for the next iteration of data collection to better reflect that “Catastrophic” refers to the effect on the overall process and not to individual elements of the process.

In looking more deeply into some of the students’ reported “actual” consequences, as well as their predicted “potential” consequences, it became clear that although students were quite able to correctly identify hazards, their assessment of the consequence levels was not always accurate. For example, students at one university reported that the absorption column they were using had flooded and identified this as a potentially “Catastrophic” process consequence. In reality, the column is designed to be able to be flooded safely—piping allows the liquid coming out of the top to go directly to the room drain. Furthermore, students in this activity were asked to determine the safe range of operation, implying that they might, in fact, flood the column (while using water and air only) to determine where the flooding point is for various gas and liquid flow rates. Thus, reporting that the potential consequence of flooding would be “Catastrophic” is not accurate, as there are equipment safeguards in place to allow for such an event. A similar example occurred when students at another university reported that the gloves they were wearing were not compatible with the chemicals being used. However, the gloves were certainly compatible with the chemicals in the context of the activity; the only way in which the gloves would have not been sufficient protection would have been if the students submerged the gloves in the chemicals for an extended time (which they had not done and would not be doing). More concerning was that students, at times, underestimated the consequence level. In one instance, a student reported inhaling volatile chemical fumes, causing them to feel light-headed; they identified this incident as a “Near Miss”. Because of these types of mis-identifications, the authors feel that adding some sort of “calibration” activity to the beginning of the course could be critical to enhancing students’ understanding of consequence levels.

Pre- and Post-Surveys

Pre- and post-surveys were administered at the beginning and end of the semester to look at student understanding of key process safety-related terms and student gains due to the incident reporting structure. To normalize for student knowledge due to internship experience, students were asked to identify their internship and research experience. Response rates and internship/research experience from the study are reported in Table 2.

Response rates were 55% and 24% for the pre- and post-tests, respectively. Across all institutions, over 60% of students had completed one or more internships prior to taking the lab course. Only about 10% of students had never completed an internship or lab experience. While there were some differences in the percentage of students completing internships/lab experiences across schools, no significant differences existed between the pre- and post-test student populations.

Table 2. Response rates and frequency of internship or research experience in pre- and post-semester survey.

Self-Reported Student Experiences	Frequency	
	Pre-Semester Survey	**Post-Semester Survey**
Single Internship	33.1%	36.8%
Multiple Internships	30.1%	36.8%
Lab Experience	61.4%	54.4%
Other	1.8%	2.9%
None	11.4%	5.9%
Number of Responses (Response Rate)	166 (55%)	68 (24%)

On the pre- and post-surveys, students were asked to evaluate how well they thought they understood the following terms: risk assessment, consequence, frequency, personal safety, process safety, and environmental safety. Aggregate data from pre- and post-surveys were compared using a Mann-Whitney test for (a) all students, (b) only students who had completed internships, and (c) students who had never completed internships (this includes the responses of lab experience, other, and none). For this test, a p-value < 0.05 indicates a significant difference in the Likert-data distribution between pre- and post-survey data, with all shifts in distributions towards higher levels of understanding in the post-tests. p-values for all comparisons can be seen in Table 3.

For the aggregate data of all students, understanding of consequence, frequency, process safety and environmental safety were significantly shifted towards a higher level of understanding between the pre- and post-semester surveys. Interestingly, the only significant shift in understanding for students completing internships was in process safety, whereas all terms except for personal safety showed significant gains for students who had never completed an internship. These results show the potential value of the incident reporting structure in introducing students who have not completed internships to reporting structures and hazard identification techniques that are frequently learned during an industrial internship. The shifts in distributions for understanding in the no-internship student population can be seen in Figure 8.

For all process safety terms except personal safety, a significant shift in understanding towards higher levels of understanding occurred (Figure 8). Because the pre-survey understanding for personal safety was already high, the shift towards higher levels of understanding was not significant.

Table 3. Statistical analysis of Likert-scale data for student knowledge of process safety-related concepts between pre- and post-survey data. Comparisons of pre- and post-survey data were performed using a Mann-Whitney test. *p*-values < 0.05 (bolded values) indicate a significant difference with post-survey data shifting towards higher levels of understanding.

Process Safety Topic	Comparison of pre- and post-survey data		
	All Respondents	Internship Experience (Single or Multiple)	No Internship Experience
Risk Assessment	0.202	0.888	**0.019**
Consequence	**0.016**	0.146	**0.011**
Frequency	**0.032**	0.399	**0.007**
Personal Safety	0.222	0.382	0.092
Process Safety	**0.000**	**0.031**	**0.000**
Environmental Safety	**0.007**	0.075	**0.012**

In addition to identifying their level of understanding, students were asked to identify their knowledge gains on these terms based on the UO laboratory course. Likert-scale distributions for knowledge gains were compared between students who had and had not completed internships (Figure 9). p-values < 0.05 were found for all process safety-related terms, indicating a significant difference between the internship and no internship student populations.

Students that had not completed an industrial internship identified higher knowledge gains across all process safety topics than those students who had completed internships. This is likely due to the significant integration of process safety-related content during an internship program. Both student groups indicated the lowest level of knowledge gains for frequency, with 34% of intern students and 18% of non-intern students indicating no knowledge gains. These data suggest additional instructional content on frequency is a potential area of improvement for future implementation of the reporting structure. Faculty did not report the data collected to students throughout the semester, which could have aided in understanding how frequency data is collected and used in risk assessment studies. Interestingly, although the level of knowledge of personal safety reported by students did not increase (Table 3), 52% of intern students and 77% of non-intern students reported a moderate or higher level of knowledge gained (Figure 9D). Knowledge gains in process safety and risk assessment were similar, with approximately 50% of intern students and 75% of non-intern students indicating moderate or higher knowledge gains.

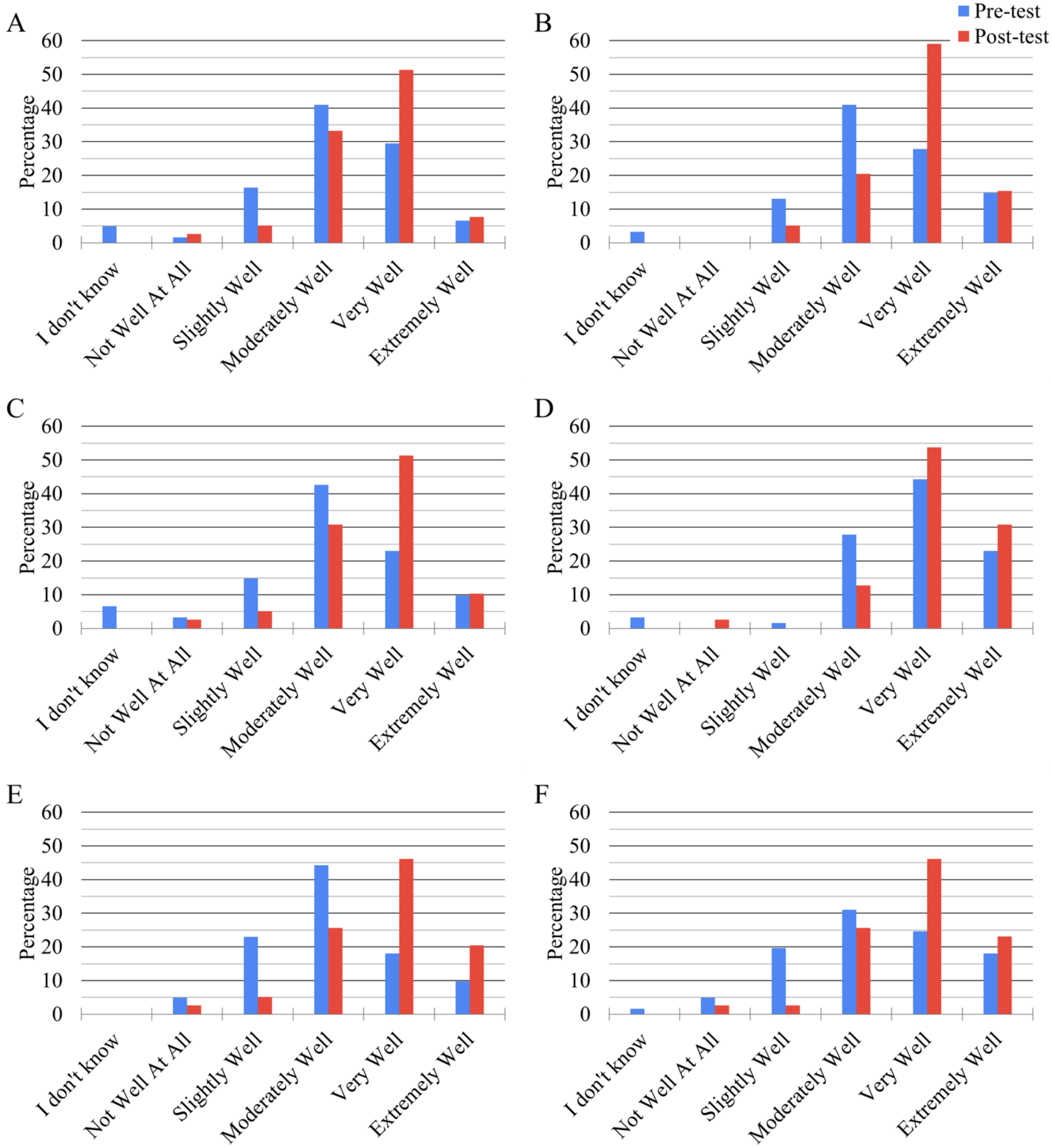

Figure 8. Shift in distributions for understanding in the no-internship population between pre- (n = 61)and post-surveys (n = 39) for (A) Risk Assessment, (B) Consequence, (C) Frequency, (D) Personal Safety, (E) Process Safety and (F) Environmental Safety.

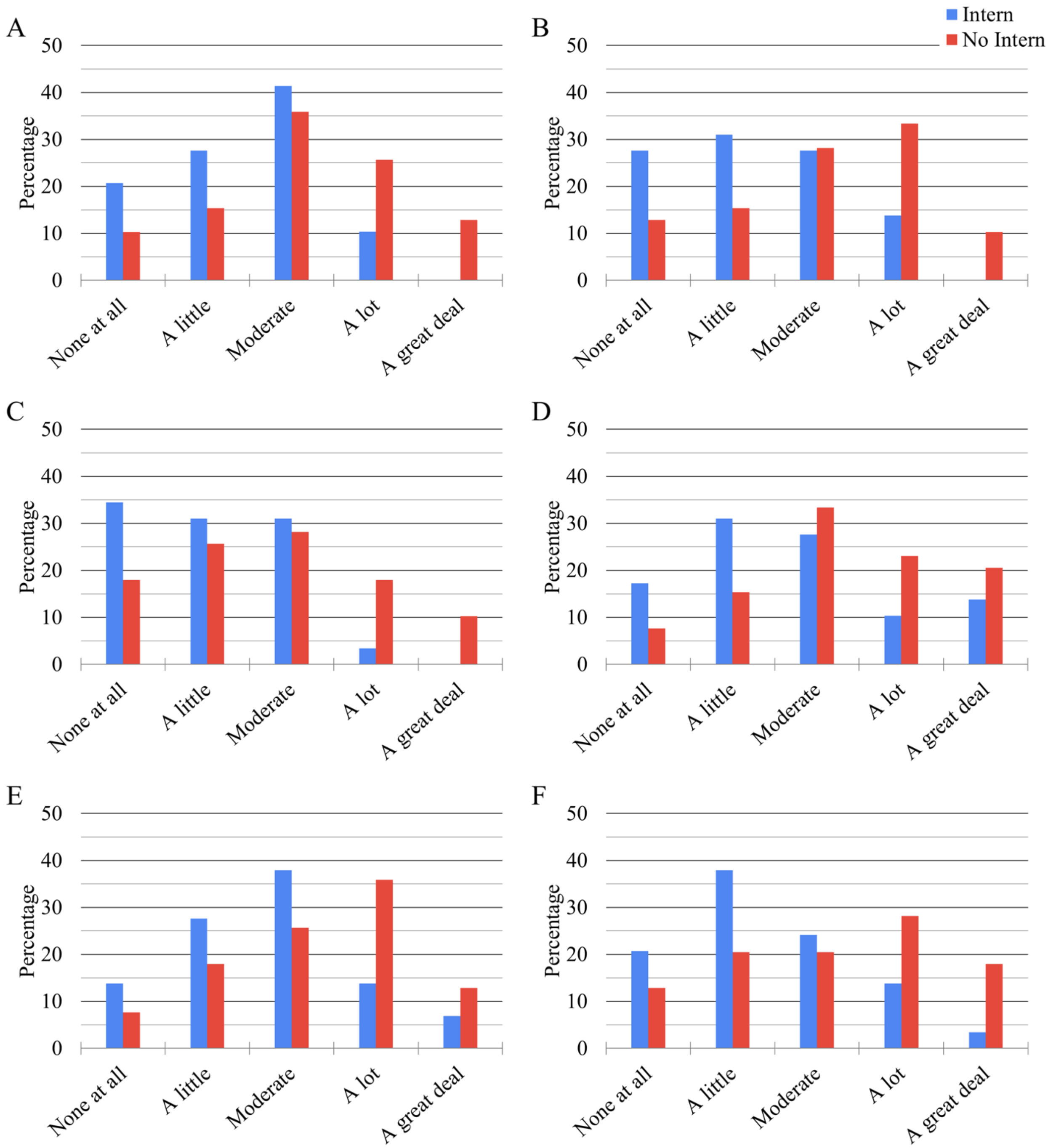

Figure 9. Likert-scale distributions of knowledge gains for internship (*n* = 29) and no internship (*n* = 39) populations for (A) Risk Assessment, (B) Consequence, (C) Frequency, (D) Personal Safety, (E) Process Safety and (F) Environmental Safety.

Conclusions and Recommendations

Through a simple implementation of a safety incident reporting structure, the authors have not only begun quantitatively benchmarking the hazards and frequencies in the UO lab, but they have also helped to teach students about risk assessment and improved overall safety culture. First, the actual consequence levels within the UO lab have been shown to be relatively minor: the UO lab is generally quite safe. Next, the incident reporting survey highlighted both strengths and weaknesses in current lab safety (e.g., good sample labeling practices but occasional failures to discuss incidents with instructors), as well as several ways in which the survey wording could be improved. Wording improvements include more clearly defining consequence levels for process-type incidents, as the current definition seems to apply to minor supplies like glassware. Similarly, several common categories of incidents were not listed (e.g., solid chemical spill, broken glass, ingestion of chemicals). Finally, students often had trouble identifying appropriate consequence levels for both actual and potential consequence, indicating that a “calibration” activity at the start of the semester could be helpful.

Pre- and post-semester surveys showed that students reported increased understanding of terms related to risk analysis and hazard identification, and the gains in understanding were more significant for students who had not completed an industrial internship. Thus, this instruction may help prepare students who have not had the opportunity to do internships for industry-relevant process safety. The weakest learning gains were for the concept of frequency, which implies that the authors should perhaps “close the loop” by having students interact with the incident reporting data to see the relative frequency of different incident types. Overall, the project was able to achieve all of its goals related to improving safety culture and understanding of risk assessment and hazard identification.

Future work will attempt to better quantify the frequency of incidents at various universities, improve survey wording, and more effectively use data collected through the study to teach these concepts to our students.

Based on this work, the authors have the following suggestions for instructors planning to implement a similar activity in their courses:

- Create a reporting structure that allows students to experience and quantify risk analysis in their lab course. This process can be especially beneficial for students who have not had prior industrial experience. A sample incident reporting structure can be viewed at this link: https://neu.co1.qualtrics.com/jfe/form/SV_0DoaoRIFrbRJcAB
- Include a calibration activity at the start of the semester to help students identify appropriate consequence levels for various categories of hazards. For example, broken glassware should not be considered a “catastrophic” event.
- Have students interact with the data they create to better understand the concept of frequency as it relates to risk analysis. For example, students could use the data to create a risk matrix.

References

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