AC 2008-322: ENHANCING THE UNDERGRADUATE CHEMICAL ENGINEERING CURRICULUM WITH AN INDUSTRIAL PROCESS SAFETY APPROACH

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Abstract

This paper summarizes the industrial process risk analysis approach that was used to enhance a chemical engineering unit operations laboratory, training the students about process safety in an inherently low-risk environment. The approach is based on more than ten years of industrial process hazards analysis experience, which includes assessing for process-related hazards and reducing process-related risks. Before the students began the experimental phase of their laboratory project, they documented that they understood the potential hazardous events related to their project. The students completed a series of Project Risk Analysis (PRA) check sheets which listed both the hazards addressed in the OSHA Process Safety Management standard (i.e., fire, explosion, and toxic release) as well as other area and personnel safety-related hazards (e.g., noise, utilities, etc.). Then the students evaluated the risks of these "worst case" events using a consequence versus likelihood risk matrix, with the consequences, the likelihood, and the risk qualitatively ranked as low, medium, or high. Before running their experiments, the students documented that the risks had been addressed and were reduced as much as is practical. They noted the design and implementation of any engineering controls, any administrative controls, and, if needed, any required personal protective equipment (PPE). The students documented awareness of potential hazards in their surroundings by documenting an area tour, as well. Whether the students continue onto graduate school or begin their careers at a plant site, this approach provides them with awareness tools that will help them ensure their safety when working in their new and potentially hazardous environment.

1. Introduction

The purpose of this paper is to describe a series of process hazards and risk analysis check sheets that were incorporated into a section of an undergraduate chemical engineering laboratory course. These new laboratory check sheets provide the students with an approach and tool for analyzing and documenting risks to ensure that they will safely handle hazardous materials and manage hazardous processes. The check sheets were developed from work that is required for high-risk industrial hazardous processes regulated under the OSHA Process Safety Management (PSM) standard 1910.119.[1] They capture and document the qualitative elements of the detailed industrial process safety approach and help train the students on safety in an inherently low-risk environment.

This paper is divided into four major sections. The first section summarizes a literature review of hazard and risk assessments used in unit operations laboratories. The second section describes the risk evaluation procedure used to ground the project teams on common safety terminology. The third section describes the protocol and the Process Risk Analysis (PRA) check sheets that are filled out by the students during each stage of their laboratory project. The check sheets are a part of a workbook that includes all the steps in the student's assignment, from defining their project's scope and its experimental design to issuing their final report. The fourth section describes some of the student's project experiences, including key safety-related learnings identified when using the protocol. The first two projects, a fluid flow system and an agitated tank system, were part of the senior-level chemical engineering unit operations laboratory; the third project, an extrusion system, was part of the senior-level polymer engineering course.

2. Literature Review

This section summarizes prior literature located at this point on safety in the chemical engineering curriculum, with particular focus on hazards and risk assessments in the chemical engineering unit operations laboratory. It was beyond the scope of this review to note the many safety references with respect to laboratory course work across the engineering disciplines (industrial, mechanical, civil, electrical, computer, and nuclear), to summarize papers discussing the development of senior and graduate level safety courses, or to note papers describing how safety is incorporated into senior level capstone design courses.

This search included reviews of proceedings from ASEE[2], references identified in the Safety section of the Teaching Resource Center in Computer Aids for Chemical Engineering (CACHE)[3], and the two safety-oriented divisions of the American Institute of Chemical Engineers (AIChE): 1) the Center for Chemical Process Safety (CCPS)[4] and 2) the Safety And Chemical Engineering Education (SACHE)[5] Program. The SACHE discussions noted programs and ideas for safety and laboratory practices in the Spring 1999, Fall 2001, April 2003 and Fall 2005 Newsletters.[5]

Other safety-oriented checklists located during this review include the following: a "Laboratory Safety Inspection Checklist" combined with a "Job Safety Analysis" form,[6] a "Health and Safety Design Considerations Project Checklist,"[7] and a "Laboratory Safety Inspection Form."[8] Although these specifically detail hazards "check sheet" protocols, none noted documentation of the essential and final step: the risk assessment.

As has been noted in an earlier paper,[9] gradual reform in the unit operations laboratory has occurred through changes that now include incorporating safety, experimental design, process and product design, device troubleshooting, ABET EC2000 criteria, environmental awareness, commercial relevance, industrial practice, and process dynamics and control within the laboratory project. Papers that discuss incorporating safety into the laboratory include Pintar[10] and Hollar.[11] Papers that discussed the documentation of safety reviews in the unit operations laboratory include Koretsky[12] and Stuve.[13] One laboratory procedure noted that students must "State safety concerns and safety measures prominently," and include this safety documentation in their "Prelab" report.[14] Another laboratory procedure included safety and hazard assessment statements that were documented through a signed "Acknowledgment Of Understanding Safe Laboratory Practices And MSDS Sheets."[15] Again, there was little, if any, mention of a risk assessment in these papers or laboratory procedures.

A "Rubric for Laboratory Experiments" that included safety was located (this rubric is useful to meet ABET EC2000 requirements).[16] However, among the five evaluation parameters under the "Design, Perform Safe Experiments" headings:

1) Design of safe, effective laboratory experiment
2) Laboratory execution according to safe, approved experimental plan
3) Understanding of how equipment works, equipment limitations, safe operation
4) Understanding of how equipment can be used to solve stated problem
5) Understanding of key variables/parameters, appropriate ranges

there was no indication of risk assessment and of its subsequent documentation.

Papers that documented risk discussions in safety reviews include Qammer[17] and George.[18] It is hoped that this paper provides additional insights and guidance for evaluating and documenting the process risk in a laboratory environment.

3. The Risk Evaluation Procedure

The risk evaluation procedure begins by defining the types of hazards and hazardous events, qualitatively defining "frequency" and "consequence," and then qualitatively determining the risk. The teams must understand and establish a common hazards-associated language before they can agree upon and subsequently develop and document their project-related risks. As these definitions were explained to the students (some of whom appeared rather impatient), it was helpful to share the similarities of their laboratory team and a project to that of band members and a concert. For a successful concert (the project), a similar approach is required by every member of the band (the team): they must tune in and be grounded on a common note (the definitions) before they begin the show (the experiments).

3.1 The Types of Hazards and Hazardous Events

This section provides an overview of the types of hazards and hazardous events documented in the students' reports. The hazardous events may affect the process equipment ("process safety"), the students themselves ("personal safety and health"), and the environment (the "area"). The students must demonstrate before they begin their experimental work that the risks associated with these events have been addressed and are reduced as much as is practical.

3.1.1 Process Safety Hazards

The process safety hazards addressed in the lab are directly associated with those identified in the OSHA PSM standard: fire, explosion, and toxic release. Fires and explosions may occur with the release of flammable or combustible materials or with equipment over-pressurization. Toxic chemicals that are handled as gases or may vaporize have the potential for toxic releases. The students must evaluate the process safety information to determine the types of process safety hazards they may have with their project (see Section 3.3 below).

3.1.2 Personal Safety and Health Hazards

The personal safety and health hazards are defined as hazards that affect the human body. These hazards may affect one or more of the following: the head, the ears, the face, the eyes, the mouth, the lungs, the body, the arms, the hands, and the feet. Although there are a number of OSHA standards that specifically address these hazards, such as hearing conservation and respiratory protection, the purpose of noting them on the check sheet is to provide the student with an awareness of the types of hazards and risks addressed by certified safety professionals.

3.1.3 Area and Environmental Hazards

The area hazards are defined as hazards that may exist from other nearby processes (their potential impact on the student's project) or hazards that may impact other nearby processes if they occur as a result of failure in their project (a potential "domino" effect). The students must prove that they are aware of potential hazards in their surroundings by documenting an area tour. This approach is similar to the "facility siting" analysis performed in routine process hazards analyses.[1] Again, it is not the purpose of this approach to perform a formal facility siting analysis: the students become aware of their surroundings and the potential for them to affect other experiments or the potential for them to be affected by events from nearby equipment failures. Environmental hazards are captured in this review, as well. The students identify how liquid or solid spills are contained or how gaseous releases are vented, if applicable to their project.

3.2 Definitions Within A Low Risk Environment

The undergraduate chemical engineering laboratory is, by design, a low risk environment. It consists of different projects, ranging from simple low-risk experiments, such as pumping water through a pipe and determining the friction factor, to more complicated higher-risk distillation processes with flammable solvents. A simple risk equation is chosen for the student's check sheet evaluation:

$$\text{Risk} = \text{Frequency} \times \text{Consequence} \qquad [\text{Eq. 1}]$$

As is described below, the students determine their "worst case" event, evaluate the event's frequency or likelihood, evaluate the event's worst case consequence, and then establish a "high," "medium" or "low" project-related risk using the risk evaluation matrix described in Section 2.2.3.

The concept of risk is introduced to the students with the following simple scenario:

Hazardous event:	Hit by a car when walking across the road
Consequence:	Killed (worst case), "High"
Frequency of 2 PM traffic:	Assume "High"
Conclusion:	Risk is "High"
Frequency of 2 AM traffic:	Assume "Low"
Conclusion:	Risk is "Low," even though no change to consequence if hit

3.2.1 Process Hazards Frequency and Consequence Definitions

The process hazards frequency and consequence definitions are summarized in Table 1. The qualitative “low,” “medium,” and “high” frequency definitions are “not at all,” “possible,” and “very likely,” respectively. The corresponding “low” to “high” consequences range from “repairable using in-house resources” (usually the lab technician) to “completely destroyed” equipment. Since the undergraduate laboratory is a “low risk environment,” it is anticipated that none of the undergraduate projects would be identified as “high risk” (see Section 2.2.3).

Table 1

Qualitative Process Hazards Frequency and Consequence Definitions

	Frequency	Consequence
High	Very likely	Completely destroyed
Medium	Possible	Repairable using external contractor
Low	Not at all	Repairable using in-house resources

3.2.2 Personal Health Frequency and Consequence Definitions

The personal health frequency and consequence definitions are summarized in Table 2. The qualitative “low,” “medium,” and “high” frequency definitions are the same from Table 1: “not at all,” “possible,” and “very likely,” respectively. The corresponding “low” to “high” consequences range from “first aid” to “fatality.” And, as is noted above, the design of the experiment should not place any of the undergraduate projects into the “high risk” category (again, see Section 2.2.3).

Table 2

Qualitative Personal Safety Hazard Frequency and Consequence Definitions

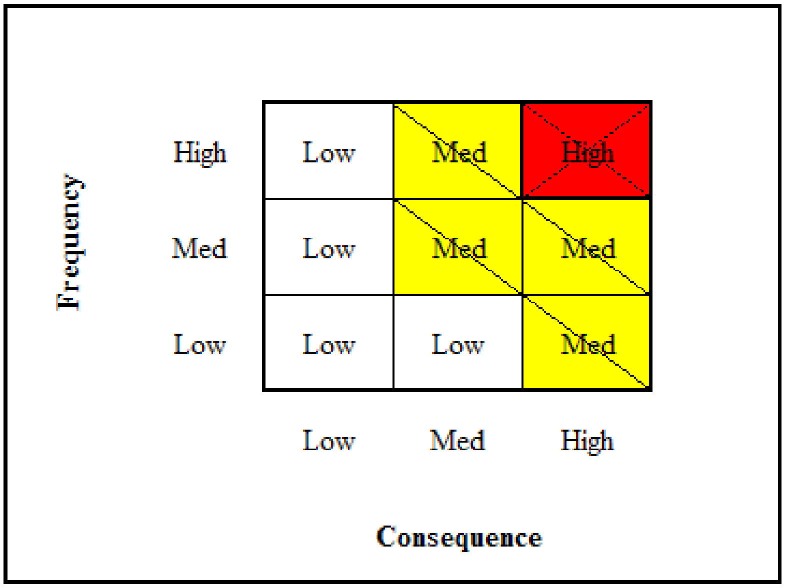
	Frequency	Consequence
High	Very likely	Fatality
Medium	Possible	Sent To Emergency Room
Low	Not at all	First Aid

3.2.3 The Qualitative Risk Evaluation Matrix

After the students agree upon the qualitative frequency and consequence of each process or personal safety-related hazardous event associated with their project, they use the qualitative risk evaluation matrix shown in Figure 1 to evaluate the project's risk. At this point it is worth noting that some definitions of "risk analysis" imply a quantitative estimate of the risk which is based on "engineering evaluations" and "mathematical techniques" when combining the estimates for the incident's frequencies and consequences.[19,20] Since the purpose of this protocol is to teach the student about the risk assessment protocol, and acknowledging that the lab already has time constraints, the risk that is assessed for their laboratory work is kept qualitative. Also note that the combination of the project's frequency and consequence for the low-risk laboratory environment should be at a "medium" risk, at worst (refer to Equation 1, the risk equation).

Figure 1

The Risk Evaluation Matrix



4. The Process Risk Analysis Check Sheet Protocol

This purpose of this section is to describe the protocol and the series of Process Risk Analysis (PRA) check sheets that are part of a workbook used to document the project's steps. The protocol, based on more than ten years of industrial process safety risk analysis experience, was easily incorporated into the existing course as the first step in their laboratory project. The check sheets were designed to help document a series of risk assessment steps, as well as provide the students with a status (tracking) report mechanism for their project.

The project's risk assessment begins with an area tour (a mini "facility siting" evaluation), assesses and documents the project's process safety information (its inherent hazards), and then concludes with the two Process Risk Analyses (PRAs). The first PRA assessment focuses on the project's "process" hazards; the second on the project-related personal safety and health hazards. The PRA check sheets are used to help identify and document potential hazardous events and their potential frequencies, consequences, and risks, providing final documentation of the means by which the risks are minimized as much as is practical. These risk minimization steps include engineering controls, administrative controls and personal protective equipment (PPE). Once these check sheets are completed, the students begin their experiments.

This section describes the workbook cover page (a project tracking or "status report" page), the project area tour (assessment one), the project process safety information review (assessment two), the project risk analysis check sheets (assessment three), the personal health risk analysis check sheets (assessment four), and concludes with a brief description of how the experimental design and oral and written reports are incorporated into the student's laboratory project ("the rest of the story").

4.1 The Workbook Cover Page

The cover page check sheet, shown in Figure 2, is used to monitor the progress and report on the status of the different assessments. Its design is for tracking and documenting the progress of the team's laboratory effort. First is an area survey to improve the student's awareness of other potential hazards in the area, as well as with the important safety procedures and equipment near their project. The second assessment focuses on the project's process safety information, which includes the material safety data sheets (MSDS), the process design basis and the equipment design basis. The third assessment focuses on the project risk analysis and is broken into three parts: the project hazards; the project risks; and the project risk controls. Assessment number four focuses on the personal health hazards, and is broken into three parts parallel to the process hazards: personal hazards; personal risks and the personal risk controls. Although not a part of the process and personal risk analyses, the cover sheet notes the subsequent required experimental design, experimental progress reports, and concludes by tracking their final written and oral reports status (completed before the end of the quarter).

Figure 2

The Student's Project Status Report Cover Sheet

		Group #
Project Title:		Members

		Status	Date
1	Area Survey		
2	Project Process Safety Information		
3	Project Risk Analysis		
	Part I - Project Hazards		
	Part II - Project Risks		
	Part III - Project Risk Controls		
4	Personal Health Hazards		
	Part I - Personal Hazards		
	Part II - Personal Risks		
	Part III - Personal Risk Controls		
5	Experimental Design		
6	Experimental Progress (Lab Notebook, Memos)		
	Day 1		
	Day 2		
	Day 3		
	Day 4		
7	Reports (Written, Oral)		

4.2 The First Assessment – The Area Survey and Tour

The area survey simulates a process area tour that is essential as the first step in any process risk analysis. The survey ensures that the students assess the location of their equipment and determine any project-related "facility siting" issues: they must understand and document the effects of their project's potential hazards on nearby equipment and personnel (students), as well as the effects of nearby hazards on their own safety. The check sheet template format, shown in Table 3, helps the students document the locations of eye wash stations, fire extinguishers, emergency exits, fire alarms, emergency phones, and the other potential area-related hazards.

Table 3

Questions Posed and Answer Format in the Area Survey

1	Area Survey	Location
	Eye Wash Stations	
	Fire Extinguishers	(Space is provided on the spreadsheet for students to fill out their responses)
	Emergency Exits	
	Fire Alarms	
	Emergency Phones - (Emergency Number)	

Other Operating Equipment in area nearby (and their potential hazards)

4.3 The Second Assessment – The Process Safety Information

The next step in a process risk analysis is identifying and documenting the process safety information. The students complete this second assessment using the check sheet format shown in Table 4. The process safety information integrates the technical knowledge of the process, its hazards of materials, process design basis, and equipment design basis. The materials used in the process and their safety information (in particular, their Material Safety Data Sheets – MSDS) must be known and understood before working with them. The process design, such as the operating pressures and temperatures, must be documented and understood. And finally, the equipment design documents, such as those ensuring that the equipment was built according to established codes and standards, must be available. The latter is termed RAGAGEP: "Recognized And Generally Accepted Good Engineering Practices."[1] Industrial practices, including the administrative controls, the standard operating conditions and the maintenance procedures rely on and are developed from accurate process safety information. Note that it is not the purpose of this check sheet to develop this information; its purpose is to train the students to make them aware that this information must be available and understood to ensure that these safe operating practices exist.

Table 4

Questions Posed in the Project Process Safety Information

Project Process Safety Information	Notes (Location of Resources)	Review Status	Date
Material Hazards Information (Types of Materials)			
Process Design Information			
Equipment Design Information			

4.4 The Third Assessment – The Project Risks

After completing the area survey and establishing a framework of their project's process safety information, the students are ready to use the Process Risk Analysis (PRA) check sheets to determine their project's risks. There are two parts to the project's risk, those related to the "process" (the project) and those related to "personnel" (health hazards). This section describes the project-related risk evaluation; Section 3.5 describes the personal health-related risk evaluation.

The project-related PRA check sheets list the hazards addressed in the OSHA Process Safety Management (PSM) standard (fire, explosion, and toxic release) and include other area safety-related hazards. Based on the definitions of the types of process hazards shown in Table 5, the students document their project hazards using the check sheet format shown in Table 6 (this is "Part I"). Then they determine the level of their project's worst case consequence and frequencies from Table 1 and determine the risk with the risk evaluation matrix in Figure 1. Each consequence, frequency, and risk evaluation for each hazardous event is then documented in the check sheet format shown in Table 7 ("Part II"). The students must demonstrate that these risks have been addressed and are reduced as much as practical before they begin their experiments. Hence, they document the design of and implementation of any engineering controls, any administrative controls, and any required personal protective equipment (PPE), as needed, using the check sheet format shown in Table 8 ("Part III"). Note that the students may add any "suggested improvements" to help improve the safety of their project, as well (this is similar to any process safety management program where the operators have a method for making suggestions).

Table 5

Definitions of the Project Process Hazards

01	Fire	Release of light, heat and smoke during material burning
02	Explosion - Chemical	A sudden formation of a large volume of expanding gas
03	Explosion - Physical	A violent burst caused by excessive internal pressure
04	Toxic Release	Gaseous release that causes physiochemical injury to living organisms
05	Steam	Heated water vapor in the air (boiling temperatures; high pressures)
06	Thermal Energy	Heat energy - transferred by temperature differences (e.g., hot materials or process conditions)
07	Electrical Energy	Electricity - available by the flow of electrons through a conductor (e.g., high voltage)
08	Kinetic Energy	Mechanical energy that a body has by virtue of its motion (e.g., high rotation rates)
09	Potential Energy	Mechanical energy that a body has by virtue of its position (e.g., suspended loads)
10	Radiation	Radiated or transmitted energy in the form of rays or waves or particles (e.g., nuclear sources)

Table 6

Answer Format in the Project Risk Analysis

Part I – Potential Project Hazards

3	**Part I - Potential Project Hazards**	
		Project Hazard
01	**Fire**	
02	**Explosion**	
…	etc.	
10	**Radiation**	

Table 7

Answer Format in the Project Risk Analysis

Part II - Project Risks

3	**Part II - Project Risks**			
		Consequence (Worst Case)	**Estimated Frequency**	**Estimated Risk**
01	**Fire**			
02	**Explosion**			
…	etc.			
10	**Radiation**			

Table 8

Answer Format in the Project Risk Analysis

Part III - Project Risk Controls

3	**Part III - Project Risk Control**		
		Types of Controls	**Adequate? (Suggested Improvements)**
01	**Fire**		
02	**Explosion**		
...	**etc.**		
10	**Radiation**		

4.5 The Fourth Assessment – The Personal Health Risks

The fourth PRA assessment focuses on personal health risks associated with their project. These PRA check sheets list the health hazards addressed in the OSHA standards and follow the same approach shown in Section 3.4 for the project's risk evaluation. Based on definitions for personal health hazard causes shown in Table 9, the students document their project-related health hazards using the check sheet format shown in Table 10 ("Part I"). Then they determine the level of their project's worst case health consequence and frequencies from Table 2 and determine the risk with the risk evaluation matrix in Figure 1. Each consequence, frequency, and risk evaluation for each hazardous event is then documented in the check sheet format shown in Table 11 ("Part II"). The students must demonstrate that these risks have been addressed and are reduced as much as practical before they begin their experiments. Hence, they document the design of and implementation of any engineering controls, any administrative controls, and any required personal protective equipment (PPE), as needed, using the check sheet format shown in Table 12 (Part III). Their awareness for the PPE requirements includes making sure that the PPE is stored properly, that the PPE fits properly, that the PPE is properly inspected (it is not damaged or defective) and that the PPE is regularly cleaned and maintained, as needed.[21]

Table 9

Definitions for the Causes of Personal Health Hazards

01	Head	Falling objects; electrical shock
02	Ears	Noise (OSHA requires less than 90 decibels of noise over an 8-hour day)
03	Eyes	Flying particles, liquids (acids, caustic), gases, vapors; radiation from welding, torching, soldering, and brazing, or other operations that emit light
04	Face	Flying particles, liquids (acids, caustic), gases, vapors; radiation from welding, torching, soldering, and brazing, or other operations that emit light
05	Mouth	Toxic chemicals (gas, liquid, solid)
06	Lungs	Toxic gases and vapors; harmful dusts
07	Body	Heat, cold (temperature extremes); radiation; chemical that absorb or burn
08	Arms	Objects that cause cuts, scrapes, punctures, or burns; chemicals that absorb or burn; or temperature extremes
09	Hands	Objects that cause cuts, scrapes, punctures, or burns; chemicals that absorb or burn; or temperature extremes
10	Feet	Objects that could pierce, be dropped on or roll over feet

Table 10

Answer Format in the Personal Hazards Risk Analysis

Part I - Personal Hazards

		Identified Personal Health Hazard(s)
01	Head	
02	Ears	
...	etc.	
10	Feet	

Table 11

Answer Format in the Personal Hazards Risk Analysis

Part II - Personal Risks

		Consequence (Worst Case)	Estimated Frequency	Estimated Risk
01	Head			
02	Ears			
...	etc.			
10	Feet			

Table 12

Answer Format in the Personal Hazards Risk Analysis

Part III - Personal Risk Controls

Health Hazard		Identified Hazard	Administrative Controls	Engineering Controls	Recommended PPE
01	Head				
02	Ears				
…	etc.				
10	Feet				

4.6 "The Rest of the Story"

The PRA is just a part of the entire laboratory project, as is shown in the student's project status report cover page in Figure 2. As was noted earlier, the students must demonstrate before they begin their experimental work that their project's risks have been addressed and are reduced as much as is practical. They must note the design of and implementation of any engineering controls, any administrative controls, and, if needed, any required personal protective equipment (PPE) in the check sheets shown in Tables 8 and 12. These steps do not take time away from their experiments, providing them with a strong safety-oriented foundation on their project before they start turning process knobs. The students complete their laboratory project after the PRA steps shown in Figure 2 with the following steps: 5) propose an experimental design, 6) note their experimental progress, and then 7) issue their findings and conclusions with reports. The next section of this paper describes the student's experiences and learnings while using these PRA check sheets.

5. The Student's Experiences and Learnings

This section describes the student's experiences using the PRA check sheets in three different laboratory projects and concludes with a description on how the students incorporated these risk analyses into their written and oral reports. The protocol, used in the Fall 2007 quarter, was used by seniors in their second undergraduate chemical engineering unit operations laboratory course and by students taking an elective senior-level polymerization course.

The learnings from five evaluations of the PRA check sheet protocol are discussed. The first four evaluations were obtained from two three-member teams in the laboratory course. These two teams completed two projects during the quarter, accounting for four of the PRA check sheet evaluations. The fifth evaluation came from a group of ten seniors in the polymers course. Improvements to the check sheets from student feedback were incorporated before the PRA protocol was used again. The author would like to add a safety-awareness educational note: some of these students have answered design-related questions with a safety-conscious comment in their subsequent chemical engineering design course. Each specific project discussion below begins with a brief project system equipment description and then covers the student's PRA-related experiences, the instructor's observations and the student's learnings.

5.1 The Fluid Flow Project

5.1.1 System Description

The fluid flow system consists of a water tank, a pump and a series of pipes of various materials, lengths and diameters. The students open and close valves to establish the water flow into the different pipes and vary the pump speed to change the water flow rate through the system. Pressure drops are measured at different water flow rates and the students use their data to calculate the Fanning friction factor as a function of the Reynolds Number.

The system is located in the "High Bay" of the chemical engineering laboratory, a two-story room containing a distillation column and other unit operations equipment with an open-railed walkway along the perimeter of the second floor (the walkway makes a great "observation deck"). The fluid flow system pipes are mounted on one of the High Bay walls, with the pump and a pipe pressure tap display panel located on the first floor.

5.1.2 Experiences, Observations and Learnings

The first assessment that the students perform is the area survey and area tour. The students document that they know the locations of eye wash stations, fire extinguishers, emergency exits, fire alarms, emergency phones, and other potential area-related hazards. They learn that this is the first step when working with any process. The area tour helped both teams identify the potential High Bay area's falling object hazard, reinforcing the hard hat PPE requirement when working in the lab. The area survey also noted the nearby two-story distillation column equipment that, when operating, contains flammable solvents.

One team documented the manometer fluid as a "mysterious fluid in gauges," and noted that the nearby drain as the "method for control" if the fluid spilled. They were not allowed to proceed and operate their equipment until they had the fluid's MSDS and ensured the instructor that the fluid's spill containment procedure prevented it from going down the nearby drain. The students learned that working safely requires that they have access to and understand all of the process safety information in the new assignment.

During one team's data-acquisition step, the instructor stood on the High Bay walkway above their equipment for several minutes before being noticed by the students below. The students learned that when they are in the field, they must pay attention to their surroundings – especially if personnel are working overhead.

Both teams determined that the process hazard risks and the personal health hazard risks were low or medium, consistent with the design of the projects in the unit operations laboratory.

5.2 The Agitated Tank Project

5.2.1 System Description

This system consists of a 60-gallon insulated tank containing an agitator that enters from the top, a steam coil for heating the water inside the tank, and thermocouples at various locations inside the tank. The students vary the water flow rate into the tank (its residence time) and determine heat transfer coefficients and other Continuous Stirred Tank Reactor (CSTR) mixing-related properties when heating the tank's contents. The students open and close valves to establish the water and steam flow rates to the system.

The system is located in the corner of a room containing other unit operations equipment (a filter press, a dryer, a tank-level control system, etc.). One side of this room is open to the High Bay area noted above.

5.2.2 Experiences, Observations and Learnings

The area tour identified the crowded work space ("congestion") with the different experimental equipment. There were no system hazards noted that would affect nearby equipment; nor were there any nearby process hazards identified that would affect the agitated tank system (no "facility siting" issues). However, during the third lab session, one team noted than nearby equipment was being tested that had not been addressed during their initial survey. The students learned the importance of periodic reviews to ensure that conditions have not changed (this is similar to the required five-year process hazards analysis "revalidation" schedule[1]).

The students identified the thermal hazard associated with steam. However, the first team (and the instructor) did not notice a hazardous condition: a small and exposed three-inch pipe leading to the steam's pressure gauge. A student in the first team burned his forearm on this pipe when reaching past the pressure gauge to change the steam valve. However, he did not report his burn until a week later, thinking that "it was no big deal." Once discovered, the instructor initiated the school's incident reporting procedure and communicated the incident to the other lab students (note that this step is a requirement through a PSM incident reporting system[1]).

The injured student completed the incident report and issued a "change form" requesting replacing the pipe insulation that had fallen off and had not been reported. It was interesting to note that some of other students had had "near misses" with the exposed pipe stem earlier but had not reported the unsafe condition ("yes, we knew the exposed pipe was hot"). This incident provided a great opportunity to share with the students the concept of the "near miss:" it is only a matter of seconds or centimeters that prevents the near miss from being an injury or incident. If the near miss had been reported, the unsafe condition could have been addressed and fixed before it caused the injury. The students learned that reporting near misses is a proactive approach to improving safety. The students learned the importance of reporting and learning from near misses and timely reporting of incidences --- an essential and often overlooked operating discipline inherent in effective process safety management programs.

The teams determined that the process hazard risks and the personal health hazard risks were low or medium, consistent with the design of the projects in the unit operations laboratory.

5.3 The Polymer Extrusion Project

5.3.1 System Description

The mini-extruder system is located in a room dedicated to polymer research experiments. The system consists of a hopper, a six-inch extruder, a water trough and a chipper. The parameters that could be changed included the extruder zone temperatures, the extruder's screw rotation rate and the chipping rate. The different polymer pellets extruded in the experiments included low and high density polyethylene.

5.3.2 Experiences, Observations and Learnings

Since the extrusion system is in a room dedicated to the polymer equipment, there is no "congestion" issue, as was noted during the area tour. There were no other experiments underway that affected the project. The extruder's major hazard is the burn potential if contact is made with the hot, exposed and un-insulated die or the hot melt and extrudate. There was a potential personal hazard at the chipper, as well: the sharp chipper knives could cut fingers.

The MSDS's for several chipped polymer samples located in the lab were reviewed by the students. These polymer samples were potential candidates for running the extrusion tests, however, as noted in their MSDS's, some of these polymers degraded into extremely toxic gases when overheated. These polymers could not be extruded since there was no venting system located above the extruder. The students learned that some of the polymer samples in this dedicated lab were there from other studies and were not safe to test using the current extrusion system.

It is interesting to note that one of the students commented in their course evaluation that "the hazards and risk analysis process took too long." The instructor was not surprised with this comment, as he had heard similar comments from operators during his tenure in industry. The students learned that thorough process hazards and risk analyses take time – that safety analyses cannot be rushed (note the "impatient" comment above when trying to ground the students on the safety terminology (Section 2)).

The students determined that the process hazard risks and the personal health hazard risks were low or medium, consistent with the design of the mini-extrusion system.

5.4 The Student's Final Recommendations and Reports

As is well known to process hazards analysis leaders, a process hazards analysis is not complete until the final results and recommendations are documented and communicated to all affected personnel.[1] Hence, the final conclusions and report, whether written or a written/oral combination carried much weight in the student's final grade. This section briefly summarizes the some of the student's efforts and learnings when writing and presenting their work.

5.4.1 Written Reports

The PRA check sheets were included as an appendix in the first laboratory report and in the extrusion project report with a brief discussion of the safety review noted in the report's equipment description section. However, several students struggled with this idea, as they felt it belonged in the body of the report. They learned that industrial safety reviews are usually separate reports and that they are not normally included in experimental reports.

The second laboratory report was issued as a two-page summary report. One student included the manometer MSDS as an eight-page appendix to his fluid system summary report. His incorrect response to the instructor's inquiry as to why it was included (especially since there was no reference to it in the report): "Because you're a safety guy and you like the safety stuff." Although the instructor was honored to be called a "safety guy," the student learned that this information did not belong in the summary report (managers and supervisors will assume that you have this information) and did not include the MSDS in his re-submitted report.

5.4.2 Oral Reports

The lab teams practiced their oral reports as a "dress rehearsal" for the instructor before their class presentation. To meet the time constraints, the students had to make difficult choices on what not to discuss during their presentation. And, like the written reports, the PRA check sheets and their results were eliminated from the presentation. The students learned that the important safety understanding was inherent in their project presentation: the audience (i.e., managers and supervisors) assumes that all the safety aspects have been considered and there are no issues unless they are raised.

6. Future PRA Applications

Future applications of this approach are underway in other chemical engineering courses. Both the required senior design course and the elective senior-level safety, health and loss prevention course will benefit from this industrial PRA approach. Parts of the PRA may be used as a guide for the process design to ensure that appropriate administrative and engineering controls have been considered for the proposed process. The PRA approach is a natural fit for the safety course, which covers chemical process safety (fires, explosions and toxic release) as well as industrial hygiene (toxicology, PPE, etc.). As is expected in industry, a process hazards analysis approach addresses both the safety and health hazards: assessing for the worst case consequences, evaluating their risk based on estimated frequencies and then providing guidance on the design of engineering and administrative controls to reduce the risk. The risk reduction methods include reducing the consequences with inherently safer design, implementing engineering controls to reduce the frequency, and increasing operational discipline.

7. Summary

The students learned several important process safety concepts and experienced how these methods can affect them, even in a low-risk environment. The area tour is first: they learned that the written information does not replace actual field observations. In their review of their project's process safety information, the students learned that they must not work with a process until they understand and have access to the process safety information. They learned that administrative, engineering controls have been implemented to reduce the risk as much as is practical, and that PPE is required as a last resort to reduce risk to personnel. In their review of system's hazards, they learned that even with a formal PRA, some hazards may be missed. While they were running their project, they learned that injuries and incidents must be reported immediately and that "near misses" must be reported to help prevent future incidents. A summary of the student's Process Risk Analysis (PRA)-related learnings from the projects described in this paper is shown in Table 13; a summary of the controls implemented for their projects is shown in Table 14.

Table 13

Summary of the Process Risk Analysis (PRA) Learnings

	Project Risk Analysis Assessment Step	System			Key Process Risk Analysis (PRA)-related Learning
		Fluid Flow	Agitated Tank	Polymer Extrusion	
1	Area Survey and Tour	"High Bay" (two floors)	Congested area	Dedicated room	
2	Project Process Safety Information				Do not operate when information is missing
	Hazards of Materials	Missing MSDS	Available	Available	
	Process Design Basis	Available	Missing	Available	
	Equipment Design Basis	Available	Missing	Available	
3	Project Risk Analysis				Even with a PRA, hazards may be missed
	Part I - Project Hazards	Identified	Identified	Identified	
	Part II - Project Risks	Low and Medium	Low and Medium	Low and Medium	Risks have been reduced as much as is practical
	Part III - Project Risk Controls	Identified	Identified	Identified	There are administrative and engineering controls; PPE, as needed
4	Personal Health Hazards				
	Part I - Personal Hazards	Identified	Identified	Identified	Even with a PRA, hazards may be missed
	Part II - Personal Risks	Low and Medium	Low and Medium	Low and Medium	Risks have been reduced as much as is practical
	Part III - Personal Risk Controls	Identified	Identified	Identified	There are administrative and engineering controls; PPE, as needed
5	Experimental Design	Friction factors	Heat transfer coefficient	Polymer properties	
6	Experimental Progress (Notebook, Memos)	Status reports	Status reports	Status reports	Report incidents immediately; report unsafe conditions
7	Reports	Issued	Issued	Issued	
	Written (Draft; Final)	Completed (Group)	Completed (Group)	Completed (Individual)	Report only pertinent safety results, if applicable
	Oral (Dress rehearsal; Final)	Completed (Group)	Completed (Group)	N/A	

Table 14

Summary of the Project Risk Reduction Controls

	Project Risk Analysis Assessment Step	Fluid Flow	Agitated Tank	Polymer Extrusion
		System		
	Project Risk Analysis Assessment Step	Fluid Flow	Agitated Tank	Polymer Extrusion
3	Part III - Project Risk Controls			
	Administrative	Procedures; shut down pump	Procedures; shut down pumps	Manual pressure control (stop rotation of screw if pressure too high)
	Engineering	Pressure control valve; relief valve; pipe insulation	Pressure control valve; pipe insulation	Extruder relief valve
	Personal Protective Equipment	See Note Below	Thermal insulating gloves	Thermal insulating gloves
4	Part III - Personnel Risk Controls			
	Administrative	Wear PPE (noted below)	Wear PPE (noted below)	Wear PPE (noted below)
	Engineering	None	None	Ventilation system would be required if potential for toxic fumes
	Personal Protective Equipment	See Note Below	Thermal insulating gloves	Thermal insulating gloves
Note: General Laboratory PPE Requirements				
	Personal Protective Equipment	Hard hats; safety glasses; closed-toe shoes; long pants	Hard hats; safety glasses; closed-toe shoes; long pants	Safety glasses; closed-toe shoes; long pants

8. Conclusion

In conclusion, the process risk analysis check sheets enhance the student's laboratory experience, training them with an awareness of the elements of an industrial process safety management program. These new check sheets were simple to incorporate into the laboratory course, providing them with a tool that helped them improve their safety awareness when working in any new and potentially hazardous environment. To help the students understand that there is more to safety than just process safety, other area and personnel safety-related hazards are documented with the fire, explosion, and toxic release hazards, as well.

The students were introduced to a qualitative risk assessment method that helped them identify their project's process and personal health hazards, the project's potential hazardous events, and then estimate the event's potential consequences and frequencies. The PRA check sheets helped the student document their findings to ensure that they understood the risks associated with their project, and that these risks had been reduced as much as is practical with engineering controls, administrative controls and personal protective equipment. The students became more aware of the various safety issues inherent in manufacturing products and learned how risks can be understood and minimized.

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