RISK-BASED PROCESS SAFETY IN CHEMICAL ENGINEERING CURRICULUM

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The American Institute of Chemical Engineers' (AIChE) Center for Chemical Process Safety (CCPS) was formed in 1985 and has sought to provide resources to bridge process safety knowledge gaps for engineers entering and practicing in industry. In 1992, CCPS expanded the mission by creating the Safety in Chemical Engineering Education (SaChE) program to provide content for chemical engineering professors to incorporate into their curricula.[1]

Despite these efforts to provide process safety resources for both engineers and chemical engineering professors, causes of process safety incidents in industry have been linked to lack of education related to recognition and control of process safety hazards. This has led the U.S. Chemical Safety and Hazard Investigation Board (CSB) to make recommendations to both AIChE and the organization that accredits engineering programs, ABET, to add reactive hazard awareness to baccalaureate chemical engineering curriculum. The CCPS (through AIChE) and ABET responded by making suggested changes to accreditation criteria for all "chemical, biochemical, biomolecular, and similarly named engineering programs" within the Program Criteria, which became effective in 2012. In addition to working with ABET, AIChE is going beyond the intent of the CSB recommendation by providing resources that can be used to meet this specific ABET requirement. This includes working with CCPS on the Doing a World of Good campaign. This initiative is a comprehensive improvement to the process safety courses provided by the SaChE program and workshops that aim to build process safety competency with university professors.[2] In addition, CCPS published *Introduction to Process Safety for Undergraduates and Engineers* in the fall of 2016, which was intended as a standalone process safety course or supplemental process safety material for existing courses in an engineering curriculum.

While developing the outline for *Introduction to Process Safety for Undergraduates and Engineers*, the project team examined typical chemical engineering curricula and compared them to risk-based process safety (RBPS) models. A similar method was used at Louisiana State University (LSU) to introduce a more complete coverage of RBPS material in the curriculum. The process used and topics chosen for emphasis are discussed.

THE NEED FOR THE ABET PROGRAM CRITERIA REQUIREMENT CHANGE

In 2002, the CSB published *Improving Reactive Chemical Hazard Management* with the objective of determining how industry addresses reactive hazards and recommendations to reduce the number and severity of incidents.[3] The report identifies 167 serious incidents that occurred between 1980 and 2001 which resulted in 108 deaths. Among other conclusions, the report highlights how reactive incidents are often caused by inadequate recognition and evaluation of reactive hazards. Evidence of this conclusion is reinforced with industry incidents, such as the explosion at T2 Laboratories, Inc., in Jacksonville, Fla., in December 2007 where four people were killed, 13 were seriously injured, and the community was significantly impacted.

The CSB identified the root cause of the T2 incident as: "T2 did not recognize the runaway reaction hazard associated with the MCMT it was producing." A key finding from the incident was, "Most baccalaureate chemical engineering curricula in

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the U.S. do not specifically address reactive hazard recognition or management." The specific recommendation to AIChE was: "Work with the Accreditation Board for Engineering and Technology, Inc., to add reactive hazard awareness to baccalaureate chemical engineering curricula requirements."[4]

In October 2011, ABET worked with AIChE through CCPS and issued a statement to include the hazards associated with "the design, analysis, and control of chemical, physical, and/or biological processes, including the hazards associated with these processes" in accredited chemical engineering programs.[5] Many U.S. universities do not include RBPS principles in the engineering curricula.[6] This could lead to knowledge gaps in process safety for the early-career engineer.

INTRODUCTION TO PROCESS SAFETY FOR UNDERGRADUATES AND ENGINEERS

In 2012, the CSB formally commended AIChE for exceeding the recommended action to work with ABET to include hazards in undergraduate chemical engineering curricula.[7] CCPS continues work in this area with a number of initiatives including the 2016 publication of the resource book *Introduction to Process Safety for Undergraduates and Engineers*.

CCPS resource books are developed by committees consisting of industry experts in the subject and a CCPS staff consultant. The project steering team for *Introduction to Process Safety for Undergraduates and Engineers* included industry process safety experts, a university professor of chemical engineering process safety, and a chemical engineering graduate student. The team identified that inclusion of RBPS principles throughout the standard chemical engineering curriculum in addition to, or as an alternative to, adding a standalone process safety course, will meet the intent of the ABET requirement. The ABET requirement did not specifically prescribe that a standalone process safety course be developed, nor that process safety be included in specific courses in the curriculum. The project team felt the outline could be structured to do both: serve as a standalone course or be used as a reference in specific engineering courses. The target audience is undergraduates, early-career engineers, and those who teach chemical engineering. As Dickson and Crowl point out, engineering faculty may not have an adequate background in process safety.[6]

In developing the scope of *Introduction to Process Safety for Undergraduates and Engineers* so that it could be used throughout the curriculum or as a standalone course, the team wanted to avoid duplication of process safety content in existing chemical engineering curricula. Only one process safety book was identified in use at several U.S. universities—*Chemical Process Safety Fundamentals with Applications* by Crowl and Louvar.[8] Universities that use this resource cover several useful design topics, such as source models, dispersion modelling, fire and explosion prevention, and relief sizing. The team also identified that many typical U.S. chemical engineering curricula adequately cover some aspects of design such as overpressure relief, and standard equipment design and selection.

In order to define the content of the book, various global process safety regulations were reviewed to identify process safety topics that would likely be of value to early-career engineers. These include: OSHA PSM, EPAs RMP, Norma Oficial Mexicana, China's State Administration of Worker Safety process safety guidelines, and Europe's SEVESO III. In addition, IChemE chartered engineered requirements, and the CCPS 20 element process safety model content were reviewed. The team then compared these results with a review of typical existing chemical engineering content to ensure that the intent of the ABET criteria would be met with the book.

The study identified that a curriculum that includes understanding hazards and risks attempts to meet the intent of the ABET requirement and be of use to early-career engineers. In addition, there are other aspects of the CCPS 20 element process safety model that would be of use. CCPS groups process safety elements into four pillars: commit to process safety, understand hazards and risks, manage risks, and learn from experience.[9] The CCPS process safety pillars and elements are shown in Table 1.

TABLE 1
The four pillars and 20 elements of risk-based process safety

Commit to Process Safety	Understand Hazards and Risks	Manage Risks	Learn from Experience
Process safety culture	Process knowledge management	Operating procedures	Incident investigations
Compliance with standards	Hazard identification and risk analysis	Safe work practices	Measurements and metrics
Process safety competency		Asset integrity and reliability	Auditing
Workforce involvement		Contractor management	Management review
Stakeholder outreach		Training	
		Management of change	
		Operational readiness	
		Conduct of operations	
		Emergency management	

TABLE 2 Process safety throughout the curriculum	
Course	**Possible Process Safety Topics**
ChE Survey (Introduction)	Introduction to risk-based process safety
Material & Energy Balances	Material transfers
Numerical Methods	Probability analysis
Fluids	Source models, rotating equipment hazards, mechanical integrity
Heat & Mass Transfer	Fixed equipment hazards
Engineering Materials	Material of construction selection
Heterogeneous Equilibrium	Reactive chemical hazards
Unit Operations	Inherently safe technology/design, equipment hazards
Unit Ops Lab	Process hazard analysis, management of change, operating procedures
Kinetics	Reactive chemical hazards
Control Systems	SIS systems, SIL interlocks, availability, probability of failure
Plant Design 1	Consequence assessment (source models, dispersion models, fires & explosions)
Plant Design 2	PRD design/ inherently safe design

TABLE 3 Content of *Introduction to Process Safety for Undergraduates and Engineers*		
Chapter	**Title**	**Topic**
1	Introduction	Book organization, intended audience
2	Process safety basics	Introduction to the 4 pillars and 20 elements of process safety
3	The need for process safety	Historical process safety incidents categorized by element
4	Process safety for engineering disciplines	Definition of typical disciplined involvement with process safety
5	Process safety in design	Hazards associated with equipment design
6	Course material	Process safety topics for use throughout the ChE curriculum
7	Process safety in the workplace	Early-career engineers involvement with process safety
Appendix		Example RAGAGEP, CSB resources, reactive chemical checklist, SAChE course list, and reactivity hazard evaluation tools

To avoid duplication of existing material and include elements of RBPS in a typical curriculum, the team developed a matrix consisting of typical chemical engineering courses and the CCPS 20 element model of process safety. Table 2 illustrates the results of this study and possible topics from RBPS that could be included throughout a typical chemical engineering curriculum.

It was beyond the scope of this book to include all topics. Therefore, the team focused on content designed to familiarize the student with RBPS emphasizing the elements of risk: what could go wrong, how bad can it be, and how frequently it might occur. Table 3 lists the final scope and includes the chapters and topics included in *Introduction to Process Safety for Undergraduates and Engineers*.

DEVELOPING THE CURRICULUM CONTENT AT LSU

A separate course could be developed for each of the 20 elements of RBPS, but this is obviously not feasible. Since the CSB linked the causes of many process safety incidents to a lack of education on recognition and control of process safety hazards, the focus should be on the pillar, understanding hazards and risks, which is shown in Table 1. LSU has adopted the approach of providing a focus on understanding hazards and risks and providing supplemental process safety topics throughout the curriculum.

As industry improves and fewer process safety incidents occur, we find many early-career engineers may not have ever witnessed a process safety event and may not for years into their career, if ever. While this trend is good for industry, it is difficult to impress the importance of understanding hazards and risks without first hand understanding the consequences of incidents.

For students to gain a full appreciation and understanding of hazards and risks, introductory and supplemental topics should be covered. Suggested introductory topics include establishing the need for process safety by first defining process safety basics and reviewing historical incidents that define process safety, and reviewing the CCPS four pillars and 20 elements.

Risk assessment involves identifying what could go wrong, and determining how bad it could be and how frequently it could occur.[10] Therefore, engineers must have exposure to some fundamentals to determine the hazard consequence, severity, and frequency of events. These fundamentals include

TABLE 4 Outline of course content for introduction to risk-based process safety		
Outline	**Topic**	**Detail**
Introduction	Establish the need for process safety	History, definitions, review of major incidents and causes
	The 4 pillars and 20 elements of process safety	Introduction to risk-based process safety
	LOPC, hazards and risks	Define process safety incident, hazards, and risks
What could happen?	Process safety in design	Common equipment hazards
	Introduction to flammability	Definitions and introduction
	Reactive chemical hazards	Introduction to reactive incidents
	Hazard assessment: checklist and HAZOP	Methodology to identify hazards and risks
How bad could it be?	Consequence assessment	Source models
	Toxic release and dispersion modeling	Dispersion models
How do we mitigate risks?	Mitigating risks: LOPA	Methodology to mitigate hazards and risks
	Inherently safe technology	The tenants of inherently safe technology in design
	Learning from incidents	Root cause analysis, causal factors

understanding common equipment hazards, reactivity hazards, flammability, and source and dispersion models.

With these topics in mind, a process safety course outline shown in Table 4 was established at LSU to focus on understanding hazards and risks and meet the intent of the ABET requirement.

The introductory lectures establish the need for process safety for chemical engineers by defining process safety; contrasting process and occupational safety; and describing incidents that define process safety practices and regulations. The incident descriptions include a timeline that shows how key incidents have led to global regulations such as OSHA PSM and the European Union SEVESO Acts. The incidents reviewed in detail include: 1974 Flixborough, 1984 Bhopal, 1989 Phillips 66 Pasadena explosion, 2005 BP Texas City, and the 1990 ARCO Channelview explosion. Material for several other incidents including the instructors' personal experience such as the 1994 isocyanate overpressure fatality in Lake Charles is given in an attempt to personalize these historic events. Although the watershed incidents are covered in *Introduction to Process Safety for Undergraduates and Engineers*, supplemental material is taken from *Incidents that Define Process Safety*,[11] and additional reading is given from sources such as IChemE's *Remembering Bhopal*.[12] One lecture is devoted to the industry standard definition and classification of process safety incidents and follows the American Petroleum Institute Recommended Practice 754 (API RP 754).[13] The CCPS Process Safety Incident Evaluation desktop and electronic application tools are reviewed to aid the student in understanding classification.[14] The student is also exposed to using process safety information in order to identify hazards. This includes but is not limited to the use of safety data sheets (SDS) to identify chemical hazards, and calculating a maximum intended inventory of a process.

The remaining lectures focus on the elements of risk: what could go wrong, how bad can it be, how frequently will it occur, and how to mitigate risk. The second series of lectures—that focus on what can go wrong—concentrate on equipment hazards, flammability, and chemical reactivity. Equipment hazards for common unit operations such as pumps and compressors; heat exchangers; and reactors are discussed. Due to time constraints, the flammability lecture only covers definitions. However, the student is expected to apply concepts such as minimum oxygen concentration, upper and lower flammability limits, and autoignition temperature. In chemical reactivity, the student is expected to: create a chemical reactivity spreadsheet using the CCPS reactivity spreadsheet tool[14]; identify chemical reactivity hazards following the screening tool found in Essential Practices for Managing Chemical Reactivity Hazards[15]; understand NFPA's fire protection guide to hazardous materials; and use the CAMEO chemicals database[16] and NIOSH Pocket Guide to Chemical Hazards.[17] These tools are chosen as they are commonly used in industry to evaluate chemical reactivity hazards. This series of lectures is given with an introduction to methodology that helps students define what could go wrong in a chemical process. The primary methodology discussed is Hazard and Operability Study (HAZOP). Students are expected to use either methodology in their design project to define what could go wrong with alternatives.

Once the student can determine what could go wrong in a process, the third series of lectures introduces the students to methodology to determine how bad a scenario could be. This is done with an introduction to source and dispersion models. In addition, the student is exposed to consequence and pre-modeled scenario tables used in Layers of Protection Analysis (LOPA). The source models expand on mechanical energy balances covered in LSU's material and energy balance course, and includes noncompressible flow through an orifice. A simple gaussian plume model is used to introduce the students to the parameters that influence downwind concentrations from toxic gas releases.

The final series of lectures introduces the concepts of unmitigated and mitigated risk through the use of industry standard qualitative and semi-quantitative risk matrices commonly used in industry for LOPA. Lectures are developed based on scenarios found in Guidelines for Initiating Events and Independent Protection Layers (IPL) in Layer of Protection Analysis.[18] Example independent protection layer credits are used to mitigate the scenarios presented in class. The last two lectures emphasize mitigation techniques and inherently safe design.

The student is exposed to the same tools used in industry to identify and mitigate risk including: use of process safety information including SDS and calculating maximum intended inventory; qualitative and semi-quantitative risk matrices; use of pre-defined consequence and pre-modeled scenario tables; identification and use of initiating event frequency tables; IPL credit tables; and other HAZOP/ LOPA tools.

TEACHING PROCESS SAFETY

Fortunately, there is abundant material available to supplement lectures on process safety. In addition to those referenced here, other resources to supplement each of the topics listed in Table 4 can be found at CSB, CCPS, IChemE, and the UKs Health and Safety Executive websites, just to name a few.

LSU chose an approach to include the content shown in Table 4 in the first of a three-course plant design series. The first plant design course is taught at the junior level. The material is coupled with engineering economics and optimization, as engineers must often consider the three when making design decisions. Thirteen of 38 1-hour lectures are devoted to process safety.

It is a challenge to include so many process safety concepts in one-third of a 3-semester-hour course. To address this, LSU plans to move some content out of the plant design course and spread it throughout the curriculum similar to the illustration shown in Table 2. Beginning in the Fall of 2018, chemical reactivity hazards is covered in heterogeneous equilibrium, and source models is covered in material and energy balances. This will free up time in the plant design course to have a larger emphasis on HAZOP and LOPA. LSU will continue to develop the strategy of process safety throughout the curriculum and perhaps include unifying themes and problem sets that tie in the process safety sections of each course. However, it is too early in the process to describe this strategy in detail.

MEASURING EFFECTIVENESS

LSU students complete a plant design project in the junior- and senior-level courses. Practical application of the process safety concepts is required in both. The junior project presents a scenario in which the student compares alternatives with different risk profiles, and net present values (NPV). The students must justify an alternative selection based on unmitigated and mitigated risk, and NPV. Included is an optimization aspect for the alternatives. The students are required to complete HAZOP and LOPA analysis to identify unmitigated and mitigated risk that includes: a maximum intended inventory, a chemical reactivity matrix, a consequence assessment of worst-case scenarios, a description of the engineered and administrative controls to mitigate the risk, an analysis of inherently safer design, and justification of selection based on the risk analysis. The senior plant design project is the design of a process and in 2018 included the same process safety requirements. The 2017 seniors were not required to include this level of detail with the process safety analysis as process safety was first introduced in the curricula in spring 2017.

Each year, LSU has volunteers from industry and department faculty evaluate both the junior and senior projects by using a 5-point Likert scale, with 1 corresponding to "weak" and 5 corresponding to "strong." In 2017, the total number of evaluations was 354 and 334 for senior and junior projects, respectively. Of the 17 project evaluation criteria utilized, one is applicable for measuring process safety: recognition of OSHA process safety management considerations. This legacy evaluation question reflects the pre-process safety introduction of RBPS to the curricula and by itself is inadequate to fully measure process safety effectiveness. The rubric was modified in 2018 and discussed below.

The legacy question is used to compare the project considerations of process safety between juniors and seniors. A summary of the evaluations is shown in Figure 1.

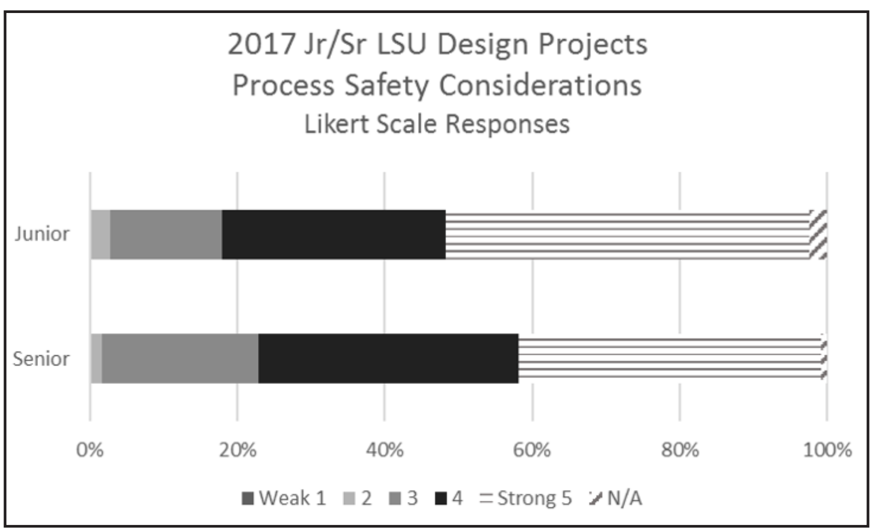

Figure 1. Process safety evaluation of junior-senior design projects.

There was a difference in evaluation scores between juniors, who received process safety educational content in their coursework, and seniors, who did not. Eighty percent of junior process safety evaluations were 4 and 5, which indicates that the projects demonstrated strong recognition of process safety considerations. This compares to 76% of senior evaluations that scored 4 and 5. Forty-nine percent of junior responses were 5 compared to 41% of seniors. A designation of NA is given if the industry representatives chose to not score this question. The data indicate junior projects included a stronger consideration for process safety than those of seniors, who had not been exposed to RBPS. However, there is not a wide spread between the data as might be expected. This is most probably due to the inadequacy of the evaluation criteria and the lack of experience in evaluating process safety by the industry representatives.

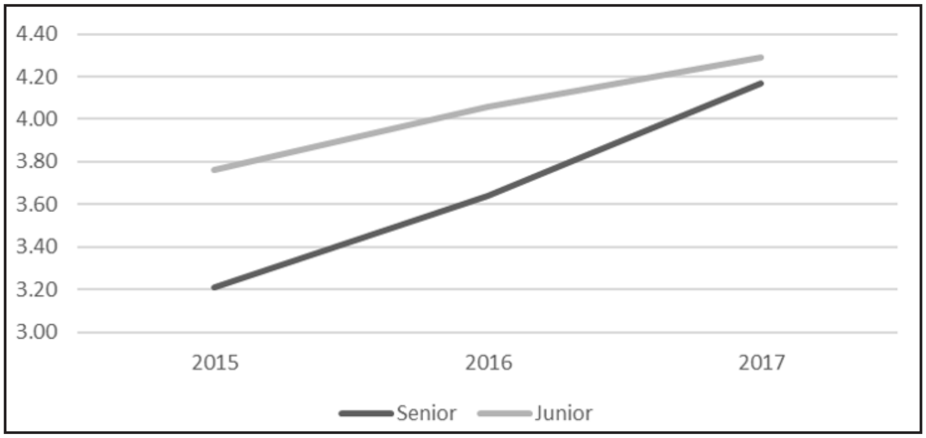

Figure 2. *Weighted average Likert response to process safety considerations.*

A brief historical view of weighted average Likert responses to the legacy process safety question is shown in Figure 2. Both classes are trending toward stronger process safety considerations with the junior-level projects averaging slightly stronger than seniors for this time period. It should be noted that the same weaknesses identified for Figure 1 apply to Figure 2.

The problem of inadequate process safety evaluation was addressed in 2018 by including several relevant questions in the rubric. In addition, guidance on how to evaluate process safety were provided to the industry representatives in fall 2018. The additional evaluation questions are shown in Table 5.

TABLE 5
2018 Process Safety Evaluation Questions

Evaluation Questions
Identifying major process hazards, performing a risk assessment, and identifying actions that must be taken as a consequence, including actions that would make the design "inherently safe."
Create a reactive chemical matrix for the chemicals involved in the alternatives and gather other pertinent process safety information for your design (*e.g.*, MSDS, materials of construction, etc.).
Create a maximum intended inventory for your alternative designs.
Using HAZOP methodology, identify a worst-case scenario and define at least one initiating event for each alternative.
Using LOPA methodology, identify the unmitigated risk on a semi-quantitative risk matrix and propose safeguards to mitigate the risk to at least "C."
Choose the design alternative that complies with the process safety requirements and has the lowest net present value cost.

CONCLUSION

Traditional chemical engineering curriculum includes process safety with some aspects of design. RBPS typically is not covered. In order to meet the 2012 ABET requirement to include hazards of the process in the curriculum, content on understanding hazards and risks should be considered. Use of process safety information such as SDS and tools used to identify chemical reactivity hazards benefit students in helping to identify what can go wrong in a process. Source and dispersion models can help students identify how bad an incident could be. Understanding HAZOP and LOPA methodology prepares the students for participation in process safety early in their careers.

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