What should every graduating chemical engineer know about process safety and how can we make sure that they do?

Dr. W. David Harding, University of New Haven

W. David Harding is a Professor of Chemical Engineering and Associate Dean for Faculty Affairs and Accreditation in the Tagliatela College of Engineering (TCoE) at University of New Haven. He has more than twenty years of academic experience after spending nine years in chemical manufacturing and environmental consulting. He has been an active participant in the Multidisciplinary Engineering Foundation Spiral Curriculum (MEFSC) efforts in TCoE and the Program to Integrate Technical Communication Habits (PITCH) initiative.

Mr. Brian Harding, Mary Kay O'Connor Process Safety Center Texas A&M University

Brian Harding is a PhD candidate at Texas A&M University. His advisor is Dr. M. Sam Mannan in the Mary Kay O'Connor Process Safety Center. His main research topic is the use of Decontamination Foam for Chemical Spill Containment. He has also worked on a variety of different safety related projects such as the investigation team for the ammonium nitrate explosion in West Texas and the use of RFID for corrosion detection in pipelines.

Mr. Peter C Montagna, University of New Haven

Peter Montagna is head of the Henkel Corporation Adhesives Division Audits & Assessments program and an adjunct instructor at the University of New Haven. Henkel Corporation is a division of Henkel KgAA, which manufactures soaps, detergents, cosmetics and adhesives for a wide variety of industries and consumers throughout the world. As Head of SHE Audits & Assessments, Peter is responsible for developing and implementing an auditing program for all Adhesives manufacturing, warehouse and laboratory sites throughout the world. The program is focused on compliance with corporate, business unit and regional SHE requirements.

Peter has taught the Chemical Process Safety course at the University of New Haven since its re-introduction in 2011. Prior to that, he was the adjunct instructor for the capstone design course at UNH from 2001 through 2004.

Peter holds degrees in Chemical Engineering from Michigan Technological University and Yale University, and is a Certified Safety Professional, Certified Professional EHS Auditor and Certified EHS Trainer. He is a board member for the Auditing Roundtable, a professional organization dedicated to the development and professional practice of environmental, health, and safety (EHS) auditing.

Throughout his career, Peter has focused on process safety and its principles. He has expertise in Process Safety Management and extensive knowledge of health and safety regulations, industry standards and practices pertaining to chemicals manufacturing.

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Introduction

Through the years, society has reaped many benefits from the chemical process industries. Imagine how different transportation would be without today's lubricants and fuels. Imagine the difficulties we would face trying to feed and care for the seven billion people on Earth without advances in farming, medical treatment and basic materials. Our lives have been positively impacted by the creativity and effort of many chemical companies throughout the world.

The chemical process industries have an excellent track record for safety. According to the Bureau of Labor Statistics, there were two injuries requiring medical treatment beyond first aid per 100 workers in chemicals manufacturing in 2013. This compares to a rate of 4.0 injuries per 100 workers for all manufacturing, and a rate of 3.5 injuries per 100 workers for all of the private sector.[1] There were an average of 1.4 fatalities in chemical manufacturing per 100,000 workers in 2013, compared to 2.0 for all manufacturing and a rate of 3.2 overall.[2] Chemical companies clearly place high emphasis on worker safety and health.

As we know, however, the chemical process industries also pose risk. The hazards of chemical processes include toxic material releases, fires and explosions. These hazards have resulted in harm to employees, the environment and in some cases the public in highly publicized events such as Bhopal and Deepwater Horizons. Risks are tolerated when hazards are controlled; when an incident occurs, the risk becomes intolerable. The public reacts negatively to events involving employee deaths, environmental damage or threats to their homes.

Incidents often result in negative publicity and a call for change. For example, a runaway reaction led to an explosion at a company called T2 Laboratories in Jacksonville, FL in December 2007.[3] The blast killed four people. Another thirty two people were injured; fourteen required treatment at a local hospital. In response, the U.S. Chemical Safety and Hazard Investigation Board (CSB) called for improvements in the undergraduate chemical engineering curriculum. Specifically, CSB recommended the American Institute of Chemical Engineers (AIChE):[4]

1. Work with the Accreditation Board for Engineering and Technology, Inc. [now known as ABET] to add reactive hazard awareness to baccalaureate chemical engineering curricula requirements.
2. Inform all student members about the Process Safety Certificate Program and encourage program participation.

AIChE's Education and Accreditation (E&A) Committee responded to these recommendations. The E&A worked with ABET to update its Chemical Engineering Specific accreditation criteria to include hazard awareness. Beginning in 2010, ABET criteria now states: "The curriculum must provide a thorough grounding in the basic sciences including chemistry, physics, and biology, with some content at an advanced level, as appropriate to the objectives of the program. The curriculum must include the engineering application of these basic sciences to the design, analysis, and control of chemical, physical, and/or biological processes, *including the hazards associated with these processes*." (emphasis added).[5] (It should be noted that the ABET Policy and Procedure Manual also requires instructional and learning environments to be safe as part of Student Outcomes and Performance Indicators.[6])

The Mary K. O'Connor Process Safety Center at Texas A&M University conducted process safety related surveys of ABET accredited Chemical Engineering Programs in 2006 and 2012.[7,8] The survey focus was to determine the number of programs offering either a core or elective process safety courses or those planning to develop such courses. Surprisingly, in 2012 only about 50% of the respondents (32% of all programs) offered a core or elective course in process safety. An additional 16 % of responding institutions indicated that they planned to develop either a core or elective course in process safety. Results from a more recent survey were presented at the AIChE 2014 Annual Meeting.[9] About one third of responding Chemical Engineering programs indicated that they have a process safety course while about one half of responding programs indicate that process safety coverage is distributed across multiple courses. A majority of respondents indicate that they utilize SACHE Safety Certificates and/or case studies.

This paper will discuss the new requirements and suggest strategies for implementing process safety into the undergraduate chemical engineering curriculum. It will provide a review of sources to help chemical engineering programs choose appropriate content and to support instruction. Suggestions for assessing the effectiveness of instruction are included to close the loop for this critically important topic.

What to Teach

As with many engineering programs, a Chemical Engineering Department must first determine what is both necessary and practical to teach. Competence in many different engineering topics is necessary for the graduate to be successful in either an academic or industrial position. It is clearly impractical to provide courses in all. Schools must determine how to implement instruction in chemical process safety while fulfilling all degree requirements.

It is instructive to review the scope of topics within Process Safety before designing an approach to teaching them. Academia can look to industry for guidance on what these topics should include. Process Safety is vitally important to chemical manufacturing companies; it has been essential for industrial practitioners for many decades. Many companies have designed and implemented Process Safety training programs that supplement the education received by a new graduate from a university Chemical Engineering program.

Process safety focuses on the prevention of toxic chemical releases, fires and explosions. Incidents can result from runaway chemical reactions, mechanical failures, maloperation or other causes. Chemical manufacturers have implemented several programs to mitigate or prevent these incidents such as hazard identification and risk assessment; mechanical integrity programs; operating procedures and operator training. Common industrial training programs include Hazard and Operability Studies; Corrosion Engineering; Writing Effective Operating Procedures; and other process-specific topics germane to an organization. The undergraduate Chemical Engineering curriculum can provide courses in these topics, or integrate these topics into existing courses to help prepare the graduating engineer for industrial practice.

In addition to proactive programs that prevent incidents, it is important to learn from past experience. In the words of George Santanaya, a famous Spanish philosopher, “Those who do not remember the past are condemned to repeat it.” Company-sponsored, post-graduation training programs are meant to fulfill these needs.

A more formal approach to deciding what process safety topics should be covered is to review the regulatory framework. Companies in the United States involved with storing, handling or manufacturing “highly hazardous chemicals” above a certain threshold are subject to the requirements of 29CFR §1910.119. This regulation is known as the Occupational Safety and Health Administration’s Process Safety Management of Highly Hazardous Chemicals (“PSM”).[10] Requirements of the regulation can serve as a framework for understanding what topics should be covered in an undergraduate Chemical Engineering curriculum. The PSM regulation has sixteen sections as outlined in Table 1.

Table 1. Process Safety Management of Highly Hazardous Chemicals, or 29 CFR §1910.119

Section	Description
Application	The regulation applies if a process involves more than a threshold quantity of a chemical listed in Appendix A, or more than 10,000 lbs of flammable material.
Definitions	Terms within the regulation are defined.
Employee Participation	Employees must have input in several elements, including process hazards analysis, operating procedures, training and incident investigation.
Process Safety Information	Information on the chemicals involved in the process, the process technology and equipment in the process must be compiled for purposes of evaluating process hazards.
Process Hazards Analysis	Process hazards and existing safeguards must be evaluated to determine whether process risk is tolerable, using an approved technique (e.g., Hazard and Operability Study).
Operating Procedures	Equipment operating and maintenance procedures must be developed and implemented.
Training	Operations personnel must be trained in the process.
Contractors	Contract employees must be trained in site-specific safe work procedures, and contract employer’s safety programs must be evaluated.

Pre-Startup Safety Review	A new or modified facility must be evaluated prior to the introduction of highly hazardous chemicals.
Mechanical Integrity	Programs must be developed and implemented to address what equipment is covered (pressure vessels, storage tanks, piping, pressure relief devices, controls, emergency shutdown systems and pumps, at a minimum); maintenance procedures; maintenance technician training; inspection, testing and preventive maintenance; managing deficiencies; and quality assurance (engineering standards, management of spare parts).
Hot Work Permits	Work involving flames, sparks or other tools capable of serving as an ignition source must be controlled through procedure and a permit-to-work program.
Management of Change	Changes to procedures, chemicals, equipment or process technology must be reviewed prior to implementation.
Incident Investigation	Any incident that could or did result in a catastrophic event must be investigated, for purposes of identifying root cause and implementing effective corrective and preventive measures.
Emergency Planning and Response	A plan must be in place to address proper response to foreseeable emergencies; employees must be trained in the plan upon initial hire, and after any substantive changes.
Compliance Audits	The PSM program must be evaluated at least once every three years.
Trade Secrets	The employer may maintain the identity of materials used in the process as confidential however their properties must be revealed to employees for purposes of evaluating process hazards.

As an example, process safety information requires the compilation of information pertaining to the chemicals involved in a process. Graduating students are expected to be able to read and comprehend a Safety Data Sheet (SDS). Further, they should understand how to access additional information generally not available on a SDS but important to process safety (e.g., chemical compatibility of elastomers and metals used in the Chemical Process Industries). The graduating student is expected to develop a process flow diagram, complete with material and energy balance – a requirement of process safety information related to the technology of the process. A thorough review of PSM will reveal topics important to process safety that a chemical engineering curriculum should consider for inclusion.

The Safety in Chemical Engineering Education organization (SAChE) recognized many of these technical needs. In February 2010 SAChE published recommendations that would prepare graduating Chemical Engineers for industry.[11] Further, these recommendations serve as guidance for addressing the ABET requirements. The eight recommendations include:

1. Understanding the importance of process safety
2. The ability to characterize hazards associated with chemicals
3. Applying concepts of inherently safer design
4. Understanding how to mitigate hazards

5. A familiarity with major safety related regulations
6. An understanding of impacts of chemical plant incidents due to releases and exposures
7. Proficiency with at least one hazard identification procedure
8. Familiarity with hazard evaluation and risk assessment

In addition to formulating these recommendations, SAChE produces training modules to support process safety instruction in universities and industry.[12] SAChE modules include:

1. Process safety management
2. Inherently safer processes/design
3. Runaway reactions
4. Chemical reactivity hazards and material properties
5. Pressure relief and venting
6. Explosion hazards
7. Chemical transportation and handling, and
8. Process hazard identification and risk analysis.

Note several other modules are available from SAChE.

These same or similar topics are discussed to varying degrees in popular textbooks used in Chemical Engineering senior design courses such as Analysis, Synthesis, and Design of Chemical Processes, 4th Ed., by Turton et al., and Chemical Engineering Design: Principles, Practice, and Economics of Plant and Process Design, 2nd Ed. by Towler and Sinnott.[13,14] There are also a few specialized texts that are used in courses dedicated to chemical process safety and other related areas. This includes texts such as Industrial Safety and Health Management by Ray and Reiske; Chemical Process Safety: Fundamentals with Applications by Crowl and Louvar, 3rd Ed., and a new e-textbook Process Safety Management: Interactive, Electronic Learning by Cutshall, Grubbe, and Swanson.[15,16,17] The Center for Chemical Process Safety also publishes several relevant sources including 1) Guidelines for Engineering Design for Process Safety, 2nd Edition, 2) Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities, and 3) Inherently Safer Chemical Processes: A Life Cycle Approach, 2nd Edition.[18,19,20]

How to Teach These Topics

Process safety topics can be covered in a dedicated course, or introduced in other core chemical engineering courses. Depending on local resources it may be easier for a Chemical Engineering Department to incorporate process safety topics into existing courses. Supplemental resources can also be of great value as discussed below. To address each of the eight recommendations from SAChE, the following ideas are provided on how to integrate into existing courses:

- The importance of process safety

The general importance of process safety should be introduced in the first dedicated chemical engineering class. Similar to the principles used in industry, process safety must be considered a value and therefore introduced early and reinforced frequently. An excellent way to begin the discussion is with the AIChE Code of Ethics, which states that, "Members shall: Hold paramount the safety, health and welfare of the public and protect the environment in performance of their professional duties."[21] This concept can be reinforced by discussing significant historical accidents and incidents in the chemical process industries. Information is available from the CSB and several books, particularly those written by Trevor Kletz (e.g., "What Went Wrong" now in its 5th edition).[22]

- The ability to characterize hazards associated with chemicals

Associated chemical hazards is a topic that can be incorporated into Chemistry classes and laboratories. At a minimum, students must be proficient at reading and understanding a Safety Data Sheet or SDS. The following sections are particularly important: Section 2, Hazard Identification; Section 4, First Aid Measures; Section 5, Fire-fighting Measures; Section 6, Accidental Release Measures; Section 8, Exposure Controls and Personal Protection; Section 10, Stability and Reactivity; Section 11, Toxicological Information; and Section 12, Ecological Information. This information must be supplemented with technical instruction; for example, the definition of flash point is critically important for understanding flammability hazards. In addition to SDS reviews, supplemental resources should be introduced that discuss corrosion (see, for example, Corrosion Handbook [23], Essential Practices for Managing Chemical Reactivity Hazards [24], and fire and explosion related information like Dow's Fire and Explosion Index[25]).

- Application of concepts of inherently safer design

Inherently safer design (ISD), sometimes referred to as inherently safer technology, is a concept that can be integrated into the capstone design course. The guiding principles of ISD include elimination, minimization, substitution, moderation, and simplification. While students develop a process design, instructors should present examples of how ISD principles can or should be applied (e.g., eliminating or reducing the size of an intermediate storage tank and its impact on the plant on-stream factor). Alternative designs should be developed and analyzed for capital and operating cost versus risk reduction. Instructors should emphasize that designing a process using ISD initially is much simpler and easier than redesigning an existing facility.

- Understanding how to mitigate hazards

Hazard mitigation is another concept that can be discussed in the design course. Concepts may also be introduced in other engineering courses pertinent to the hazard involved. Hazards are inherent in any manufacturing process. Students should identify the hazards present in their design or engineering concept being studied. The basic discussion of hazard mitigation should cover engineering controls, administrative controls and personal protective equipment (PPE). It is important to stress the hierarchy of controls: engineering controls can prevent or significantly reduce the impact of a release, while administrative controls and PPE only limit exposure to a release. See hazard evaluation and risk assessment below for additional details.

- Familiarity with major safety related regulations

This is an important topic that is difficult to naturally integrate into a chemical engineering curriculum. Regulations and legal matters are rarely discussed in science or design courses. One way to present the information is to discuss watershed events that have occurred in the chemical process industry within the appropriate course, and include an overview of a regulation intended to prevent a reoccurrence. Some examples are provided in Table 2.

Table 2. Incidents in the Chemical Process Industries and associated regulatory action.

Incident	Regulation
Over 6 tonnes of hexachlorophene containing 2,3,7,8-tetrachlorodibenzoparadioxin (toxic at part per billion levels) were released outside of Milan, Italy in 1976 as a result of a runaway reaction.	Seveso II Directive
An estimated 25 tons of methyl isocyanate were released from a storage tank at a Union Carbide plant in Bhopal in 1984. Process controls, scrubbers and emergency shutdown systems all failed. Over 2,000 people died within days; several thousand more were adversely impacted by the disaster.	EPA Risk Management Plan
A release of isobutane resulted in a boiling liquid expanding vapor explosion (BLEVE) that killed 23 employees and injured over 300 at a Philips plant in Pasadena, TX in 1989.	OSHA Process Safety Management

Courses in reaction engineering or kinetics could include such a discussion. Courses that support the engineering curriculum such as technical writing and presentation skills, or introductory courses in engineering could also be used to introduce major process safety incidents and regulations.

- An understanding of impacts of chemical plant incidents due to releases and exposures

This recommendation has two aspects: chemical exposures that may be routine; and incidents. Chemical exposure concerns and toxicological effects are ideally discussed in laboratories. Students should be made aware of both acute and chronic exposure hazards for the materials they are handling. Presenting the students with Safety Data Sheets and requiring them to study a material's hazards makes it personal, and should result in proficiency. The efficacy of personal protective equipment should be included (e.g., chemical resistance of nitrile gloves). There is a broader aspect as well: does exposure to low levels of certain chemicals cause harm? Courses such as technical writing and presentation skills could be used to introduce epidemiology and the effects of chemicals on people's health. Ideally, a graduating engineer will have an understanding of the risk-reward balance we must strike to be effective.

Incidents and the resulting effects of chemical exposure can be covered while discussing major safety related regulations; see above.

- A proficiency with at least one hazard identification procedure

Process hazard identification involves identifying hazards from engineering documents. This concept should be addressed in the design course, as it is very process focused. There are a variety of tools for hazard identification; most incorporate risk assessment as part of the review. The "what-if" and "checklist" methodologies are adequate for providing a basic understanding of how events can lead to toxic material release, fire or explosion. Ideally, a piping and instrumentation diagram (P&ID) and process flow diagram (PFD) of an actual process should be used for the analysis. Material and energy balances should be performed using the PFD to confirm equipment sizing, heat transfer capabilities and utility flows. The P&ID should be reviewed to determine how critical parameters of temperature, pressure, flow and level are controlled in each piece of process equipment. Students need to practice several times to gain proficiency. Practicing engineers are often more familiar with hazard identification than faculty, and are typically very willing to guest lecture.

- A familiarity with hazard evaluation and risk assessment

Hazard evaluation (or identification) and risk assessment (HIRA) is crucial to process safety, making a basic understanding and familiarity important for engineers entering the workforce. In addition to What-if and Checklists, tools such as Hazard and Operability Study, Failure Mode and Effect Analysis (FMEA), Layers of Protection Analysis (LOPA) and Quantitative Risk Analysis (QRA) can be introduced in the design or other engineering courses. For example, FMEA could be discussed in a course on heat transfer while discussing various types of heat exchangers; LOPA could be discussed during in a course on systems engineering or controls; QRA could be discussed during a course on statistics. The design course also represents an opportunity to introduce HIRA tools, since it is the culmination of the chemical engineering curriculum and requires knowledge of all the previous process safety topics.

We should expect that a well-crafted undergraduate chemical engineering program will instill a desire for life-long learning. The graduate will receive training in additional topics appropriate to their particular industry and job function. If a program is able to acculturate students in chemical process safety, graduates are likely to seek additional education in these topics throughout their careers.

Information Sources

A wide variety of information sources are available to support the teaching of Chemical Process Safety. One excellent source is Safety in Chemical Engineering Education (SAChE) which is part of the American Institute of Chemical Engineers (AIChE) Center for Chemical Process Safety (CCPS). CCPS also provides resources to assist with the understanding and evaluation of process safety, but at a level generally above that of the typical undergraduate student. AIChE provides additional information sources such as the publication Chemical Engineering Progress (CEP) and the AIChE e-learning products. Table 3 provides a brief summary of these sources of information with detailed descriptions following.

Table 3: Summary of Major Sources of Process Safety Related Materials

Source	Description
SAChE Modules[26]	Eight modules designed primarily for use in undergraduate chemical engineering programs.
SAChE Products[12]	More than fifty items that can be used to support undergraduate chemical engineering education or practitioners in industry.
CCPS[27]	Technical presentations from sponsored symposia and process safety related webinars and guidebooks. Linked to AIChE Academy.
CEP[28]	Over 200 articles and commentaries (since 2001) related to process safety, including Process Safety Beacon (published monthly in several languages; a one page summary intended to raise awareness of a process safety topic for plant operators and mechanics).
AIChE e-learning[29]	A wide variety of e-learning courses, webinars, and conference presentations related to process safety. Easily searchable.

SAChE: SAChE has many information sources to support Chemical Engineering programs. Two are of particular interest in the university setting. The first is the SAChE Student Safety Certificate Program.[26] The Safety Certificate Program is available to all AIChE student members. Students can access the Safety Certificate Program modules online, study the materials, and complete an assessment designed to test their knowledge of the content. When the assessment has been successfully completed the student receives a certificate for that module. The designated university contact for the SAChE program also receives an end of year report listing the modules that have been completed by their students. There are currently eight SAChE Safety Certificate Program modules covering a variety of topics ranging from introduction to process safety through reactivity hazards to risk assessment and inherently safer design.

The second SAChE product of great use to chemical engineering programs is the SAChE Products archive.[12] These products have been drawn from a variety of sources. While all of the products are available for AIChE student members, department membership in SAChE is required to access the materials for use in the classroom. SAChE has recently reorganized the list of materials to show how they are linked to chemical engineering courses.

SAChE also provides access to other relevant information through their website, http://sache.org/index.asp. These include:

1) Process Safety Beacon;
2) U.S. Chemical Safety Board (CSB) video room; and
3) Dow Chemical Company Lab Safety Academy.

These sources may be of use in developing or supporting process safety education. It should be noted that some knowledgeable process safety professionals have criticized CSB videos as lacking technical substance. The videos are intended to provide information on what can happen when a process safety incident occurs. The intended audience is broad, and includes plant operators and mechanics. A more in-depth technical exploration of the underlying causes of the incident can often be found in the associated investigation report. Faculty should consider supplementing these videos with sufficient technical information to ensure engineering design issues are explored.

CCPS: CCPS is a sub organization of AIChE. The main audience of CCPS products and training materials is practicing engineers in the chemical process industries. Introducing students to CCPS is helpful in fostering lifelong learning related to chemical process safety. The CCPS has published many guidelines and other books related to process safety subjects. CCPS organizes process safety conferences annually and provides recordings of presentations through AIChE e-learning as described below. An overview of CCPS products can be found at http://www.aiche.org/ccps/resources/overview.

E-learning: AIChE provides a variety of e-learning courses and webinars that can be used to supplement process safety instruction. These are available through and AIChE online service known as AIChE Academy http://www.aiche.org/academy (formerly known as ChemE On Demand).[29] Some of these are free to AIChE Student members while others charge a small fee. These online products include the SAChE Safety Certificate Program modules mentioned previously as well as several others. Recordings of presentations from CCPS process safety conferences are accessible through the AIChE website, http://www.aiche.org/ccps/resources/chemeondemand/conference-presentations. CCPS periodically conducts webinars to address important Process Safety topics as part of the AIChE Webinar Series as well as producing recorded archives of presentations from their annual Global Congress on Process Safety.

CEP: Another valuable source of information to supplement instruction are articles published in Chemical Engineering Progress (CEP). A recent search of the online database (http://www.aiche.org/resources/publications/cep/search) indicated 213 Process Safety related items for the period 2001 – 2014.[28] While many of these are monthly Process Safety Beacons articles, many other items are available that can be used to reinforce process safety concepts.

Some Current Models

Developing a robust and sustainable approach to teaching Chemical Process Safety can be difficult. One major challenge is selecting the right person to lead the effort. Some Chemical Engineering programs are fortunate to have a faculty member who specializes in the area of Chemical Process Safety or a closely related area. Other programs are located in an area with a high concentration of chemical manufacturing or petroleum processing and can employ an adjunct instructor with significant relevant expertise who wants to impart this knowledge on undergraduate students. Unfortunately, there are many programs that do not have ready access to such expertise.

A second major challenge is that the chemical engineering curriculum is often packed with required courses in the engineering sciences, unit operations, laboratory experiences and capstone design. While one common approach to fulfilling the ABET requirements is to offer a dedicated course in process safety, many programs find it difficult to fit a three credit course into their curriculum.[8] A further disadvantage of a dedicated course for all students is the compartmentalization that comes with a separate course.[30] The concepts of process safety can be covered in context in a variety of courses, as outlined above. Integration of SAChE modules is one possible way to achieve this context. For example, in a Chemical Kinetics and Reactor Design course a SAChE module on runaway reactions should be discussed. When coupled with a unit operations laboratory safety program such as described by Vaughen this can be an effective approach.[31] A dedicated process safety course carrying one or two credits may be another option, or possibly adding a credit to an existing course to incorporate this important content.

It is difficult to determine if any consensus has developed regarding incorporation of chemical process safety into the chemical engineering curriculum. A 2012 process safety related survey of ABET accredited Chemical Engineering programs conducted by the Mary K. O'Connor Process Safety Center at Texas A&M University found that only about 50% of the respondents (32% of all programs) offered a core or elective course in process safety. An additional 16 % of responding institutions indicated that they planned to develop either a core or elective course in process safety.[8] It is impossible to assess the state of compliance with ABET criteria from this study since the survey did not inquire about other ways each program is addressing the teaching of process safety. However, those survey results could indicate poor compliance with the criteria. Results from a more recent survey were presented at the AIChE 2014 Annual Meeting.[9] About one third of responding Chemical Engineering programs indicated that they have a one, two, or three credit process safety course while about one half of responding programs indicate that process safety coverage is distributed across multiple courses. A majority of respondents indicate that they utilize SACHE Safety Certificates and/or case studies.

The surveys mentioned here focus on the components of a process safety program and it is difficult to get a sense of how institutions are integrating these components. We can look at how some well-known programs (those with recognized chemical process safety faculty) are addressing process safety in their curriculum to gain an understanding of this integration. In a webinar presented February 6, 2013, Kimberly Ogden and Thomas Spicer provided an overview of the ABET requirements and presented details of the approached taken by University of Arizona, University of Arkansas and Northeastern University.[32] The University of Arizona incorporates several of the SAChE modules into disciplinary courses beginning with their Material and Energy Balances course and extending to the senior design courses. All students are required to complete an online laboratory safety training module before working in the lab, including the completion of a Job Safety Assessment in their upper level lab. Northeastern University has incorporated extensive process safety into their senior design sequence with two courses each carrying four credits. They require students to complete safety reviews before each unit operations experiment. Further, they have a one credit "Safety Issues in Chemical Engineering" course. The University of Arkansas requires a three credit hour chemical process safety course based on the text by Crowl and Louvar.[16]

University of New Haven's Model

The Chemical Engineering program in the Tagliatela College of Engineering at University of New Haven takes a multipronged approach to the teaching of process safety. This includes integration of SAChE Modules into most required Chemical Engineering courses, safety activities in the unit operations laboratory, incorporation of safety topics in the Chemical Engineering Design sequence, and the availability of an optional Process Safety course. This approach is in keeping with the programs philosophy that integration of topics is the best approach to support learning of critical concepts and skills. This approach is also consistent with educational psychology principles that learners are better able to incorporate concepts when they are offered in context and at an appropriate level of complexity.

At University of New Haven the approach to Process Safety taken by the Chemical Engineering program mirrors two Tagliatela College of Engineering wide initiatives. One of these initiatives is the integration of technical communication, an initiative to develop written, oral and visual communication skills and professional habits in engineering students. These activities begin in the very first semester and are reinforced and extended through all four years of each program in the college. Senior design becomes the culminating experience in which students demonstrate the skills and habits acquired through experiences in targeted prior courses. Communication products are distributed across courses as appropriate, and the skills are developed at deeper and deeper levels as students progress through the years. One critical and distinctive features of this initiative is that technical communication skills are fully integrated into the content of regular engineering courses.[33] The second initiative is an integrated multidisciplinary curriculum for the first two years of most engineering programs, including the Chemical Engineering program. The Tagliatela College of Engineering believes that this approach produces engineers that are better able to function in a multidisciplinary environment. The integrated curriculum places a great emphasis on the development of professional skills in addition to engineering content. Faculty in the Tagliatela College of Engineering at University of New Haven have presented several papers at ASEE conferences describing the curriculum, including curricular design.[34,35] The focus on integration of concepts and skills throughout the Chemical Engineering curriculum has been applied to the teaching of chemical process safety as discussed below.

A culture of safety is another important factor in the teaching of chemical process safety. At University of New Haven this begins in the first year of study in the Chemistry laboratory. The

Chemistry program has developed a comprehensive set of safety standards and a robust training program. All laboratory instructors and student assistants undergo training before entering the laboratory with annual refresher training. Every student must complete safety training at the beginning of each semester before being allowed into the laboratory. Coupled with strict enforcement, this develops a culture that laboratory safety is important. This extends to the basic safety practices in the Chemical Engineering unit operations lab. While there is a difference between personal safety in the laboratory and process safety, both are influenced by safety culture and attitude as noted in Process Safety Beacon and quoted here.[36]

> "Good personal safety performance does not ensure good process safety performance. While there is much in common, such as a good safety culture and attitude, good process safety performance requires a thorough understanding of the specific hazards associated with the chemicals being handled or stored, and the process operations being carried out in a particular plant." [36]

It is the place of the Chemical Engineering curriculum to provide the understanding of process operations and process hazards to complement the common attitudes.

The Chemical Engineering program has elected to utilize the SAChE Student Safety Certificate Program as a component of our Process Safety program. The eight current safety modules are linked to required courses in the curriculum as detailed Table 4. With the AIChE Startup initiative student membership is free and this student membership gives the students access to the SAChE modules.[26] The appropriate SAChE modules are assigned in class and the students complete the modules on their own. Instructors may choose to follow up with in class discussions or testing as well. A report listing the modules that students have completed is available from SAChE. In addition to the Student Safety Certificate Program, SAChE has available more than fifty additional products that can be used to supplement instruction (see complete list of SAChE Products)[12]

Table 4: Mapping of SAChE Modules to Required Chemical Engineering Courses at University of New Haven

Semester	Course	SAChE Module
4	Process Analysis	Process Safety 101
5	Transport Operations I	Process Safety Lessons Taught from Experience
5	Chemical Kinetics and Reactor Design	Runaway Reactions
6	Transport Operations II	Safety in the Process Industries
7	Chemical Engineering Laboratory	Risk Assessment
7	Chemical Engineering Design I	Chemical Reactivity Hazards
8	Mass Transfer Operations	Dust Explosion Control
8	Chemical Engineering Design II	Inherently Safer Design

In the unit operations laboratory students are presented with chemical process safety concepts in three ways. First, students are instructed in laboratory safety just as they have been in their prior chemistry laboratories. This stress that laboratory safety is important in all laboratory environments where chemicals are handled. Second, the SAChE Module on Risk Assessment is linked to the course. Since there are inherent risks associated with operation of the unit operations laboratory equipment this is a logical course to link. Third, students are required to perform a Hazards and Operability review of an experiment in the unit operations laboratory, including proposing measures to mitigate hazards. The instructor provides guidance in advance to allow the students to carry out the review. Students are currently required to perform an informal Job Safety Analysis before experiments. The chemical engineering program is likely to formalize this requirement in the future.

The culminating experience for chemical engineering students at University of New Haven is a two semester Chemical Engineering Design course sequence. In the first semester all students are given instruction in process safety, inherently safer design, and hazard analysis. The students complete exercises where they develop a process flow sheet and subsequently perform a safety analysis for the process. This allows the instructor to assess the level of understanding of the individual student.

The University of New Haven is one of the schools that has also developed and implemented a specific course related to process safety. Topics include:

- an overview of pertinent environmental and occupational safety & health regulations in the United States;
- fundamentals of toxicology and controls (engineering controls, administrative controls, personal protective equipment);
- modeling releases;
- reactive chemicals;
- fires and explosions;
- pressure relief;
- risk assessment, including Hazard and Operability Study;
- Accident/incident investigation; and
- Safety Instrumented Systems and Inherently Safer Technologies.

The intent of this 3-credit course is to expose students to a variety of process safety topics. Problem-solving is included in some topics, while other topics are presented in a survey fashion to help manage student work load. The course is open to senior Chemical Engineering students, and has recently become a required elective for students matriculated in the Fire Protection Engineering curriculum.

Student Outcomes and Performance Indicators

For Chemical Engineering programs, Chemical Process Safety is mandated in two ways in the ABET criteria. First, ABET General Criterion 3, Student Outcome (c) refers to consideration of safety as one “realistic” constraint in design. Second, the ABET program specific criteria for Chemical Engineering specifies that graduating chemical engineering students should know about the hazards associated with typical chemical engineering processes. ABET General Criterion 3, Student Outcomes (f) … professional and ethical responsibility … and (h) … impact of engineering solutions … are also relevant to Chemical Process Safety. From these student outcomes a set of performance indicators need to be developed to measure achievement.

Table 5 provides a set of suggested performance indicators that a program can adapt to their needs. These are related to ABET Student Outcomes c, f and h, and to the ABET program specific criteria for Chemical Engineering.[5]

Table 5: Suggested Performance Indicators Related to Process Safety

Suggested Performance Indictor	Related Course
Students can identify potential hazards from a process flowsheet (analyze process flowsheet)	Design
Students can describe the steps in a Hazards and Operability Review	Design
Students can propose layers of protection to mitigate process hazards	Design
Students can describe conditions that are likely to lead to a runaway reaction	Chemical kinetics and reactor design
Students can analyze a chemical reaction scenario to determine potential for runaway reaction.	Chemical kinetics and reactor design
Students can determine the hazards associated with operation of laboratory equipment and propose measures to mitigate (or manage) hazards.	Unit operations laboratory

Conclusion

Producing chemical engineers with the necessary training to design and operate chemical processing facilities in a safe and effective manner is critical to the profession. The chemical process industry will not continue to thrive without maintaining the trust of the general public. There is risk to the entire industry if our graduates do not consider the hazards associated with operations and work to mitigate those hazards. The teaching of process safety concepts is part of the solution to mitigate these risks.

The authors believe that the specific approach taken to the teaching of chemical process safety must be tailored to the institution's culture and needs. It should build on the inherent strengths of the institution and the availability of supplemental resources. For programs located in areas with a large chemical industry presence it is reasonable to draw expertise from those industries. However, the institution must recognize that if the core faculty do not take process safety seriously their students will not take it seriously.

As chemical engineering programs undergo reaccreditation they will need to demonstrate that they are integrating this program specific requirement. The authors hope that the information presented here will serve as a resource to assist chemical engineering programs with development of an approach that fits their needs.

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