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The Incorporation of Safety throughout the Core Curriculum

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Robert Enick

Incorporation of CHE Safety in the Core Curriculum

Introduction

The Chemical Engineering curriculum at the University of Pittsburgh is composed of six semesters that follow the two-semester first-year engineering program that is common to all engineering disciplines. During the first five semesters in the CHE department, the core (i.e., pillar) CHE classes are offered in a 'block-schedule' which immerses the students into four one-hour fifty-minute classes each week, with the fifth one-hour fifty-minute class spent in a hands-on unit operations laboratory course. In their sixth semester, the Plant Design pillar course is complemented by a two-credit Safety and Ethics course. The block-schedule curriculum does not add more credits compared to a traditional curriculum, but instead uses the hours more effectively through restructuring (e.g., combining two separate thermodynamics courses offered in consecutive terms into a single thermodynamics pillar course). This provides larger blocks of time for students to actively engage in learning in the classroom with the support of the instructor and allows for a hands-on unit operations laboratory experience for five consecutive semesters for the students in parallel with their core courses.

Table 1 provides the sequence of courses and labs which make up our core curriculum. More details on the structure, evaluation, and results of these integrated curricula in chemical engineering has been provided elsewhere [A1], [A2], [A3], [A4], [A5]. The technical content of these courses and unit operation laboratories have been progressively enriched with training in safety. Lectures on safety have been added in close connection with the specific content of some of the six pillar courses. Projects have been included in several pillars for students to incorporate safety analysis and proposals.

Table 1. CHE Core Curriculum

Year (Semester)	Core course	Cr	Companion course	Cr
Sophomore (I)	Foundations in Chemical Engineering	6	Foundations of CHE Lab	1
Sophomore (II)	Thermodynamics	6	Thermodynamics Lab	1
Junior (I)	Transport Phenomena	6	Transport Phenomena Lab	1
Junior (II)	Reactive Process Engineering	5	Reactive Process Engineering Lab	1
Senior (I)	Systems Engr. 1: Dynamics and Modeling	5	Systems Engineering I Lab	1
Senior (II)	Systems Engr. 2: Process Design	5	Safety and Ethics	2

In this paper, we will describe how the department has been more intentional, to incorporate safety throughout our curriculum. The process started with the arrival of a new faculty member, over seven years ago, who required the successful completion of some SAChE (Safety and Chemical Engineering Education Certificate program) modules into their assignments, as well as safety discussions in their classroom and design project discussions. The SAChE program is a partnership between AIChE and the Center for Chemical Process Safety (CCPS), industry and academia to improve and accelerate process safety education at the university level. The program consists of three level certificates (basic, intermediate, and advanced for a total of 32 certificates which typically take 2-4 hours each to complete). At the same time, the department adopted the practice of direct assessments/continuous improvement documentation for each of our core courses, which is reviewed and disseminated by the undergraduate committee each year. This practice has provided a regular forum for the discussion of successful (and those which were not) assignments and projects and has allowed for the exchange of ideas between the faculty, as they consider continuous improvement in their courses. The result has been that more faculty have incorporated safety assignments into a larger number of courses. Below, we share some examples of what has been included in our core curriculum.

Sophomore year

In the first Pillar course, Foundations in Chemical Engineering, the focus is on Mass and Energy Balances and Separations. Over the course of the semester, discussion of safety comes in the form of in class example problems and homework problems (as identified in the textbook). These problems involve calculations associated with safety concerns (leaking tanks, tank ruptures, asphyxiation, LFL, etc.) and often require student reflections as to how the safety incident could be avoided. Similar problems are also part of the weekly quizzes and/or exam questions. In addition, in recent semesters, each class period starts with an ice breaker. The ice breaker is a short activity, typically started as students arrive in the classroom, with a random question, which allows the students to get to know one another. After the first few week of the semester, the ice breaker questions transition to topics more relevant to chemical engineering, and often include a discussion of a recent safety incident in the news.

In addition, one of the learning objectives of this course is to apply the Engineering Design Process. The design challenge requires students to design, construct, evaluate, test and report on their product, but also to develop a mathematical model to predict their product's performance. In the most recent design challenge, students designed, constructed, and tested hot air balloons [A6] – and were required to meet various design criteria and constraints. The primary design criteria is safety. Their hot air balloons are powered by a heat gun which reaches temperatures of up to 1200^{o}F – which exceeds the melting/flammability of the balloon construction materials, therefore in-class safety discussion focused on safety precautions while using the heat gun. And in the design report, students were required (among other things) to address how they considered safety, public health, and welfare considerations in the context of their design project.

As provided in Table 1, the first five of our core courses are accompanied by a corresponding unit operations type laboratory course. This course is taught by an Instructor who has over 30 years of industrial experience and ensures that our students are made aware of safety precautions in the laboratory. Each semester the instructor reviews the safety requirements of working in the lab (i.e., appropriate PPE, no food or drink, never working alone, etc.) as well as a review of the location of the safety shower, eye wash, fire extinguisher, first aid kit, emergency phone numbers, etc. In addition, all students in our department must complete and pass the EH&S Chemical Hygiene Training and successfully complete the associated quizzes. Also, the companion Foundation of CHE Lab course requires students to take the SAChE Safety Training Modules on “Lab Safety” (ELA954), and “The Importance of Process Safety.” (ELA 950). Although there are no safety lectures or projects with safety components in the Thermodynamics pillar course, the Thermodynamics Lab course requires students to complete the SAChE Safety Training Modules on “Hazard recognition” (ELA951), and “Identifying and Minimizing Process Safety Hazards” (ELA952).

Junior year

In the fall semester Transport Phenomena course, the instructor shared multiple videos to engage the class with a discussion of safety and ethical concerns associated with the design of various equipment ranging from a heat exchanger, a hemodialyzer, a parachute, a blood pressure monitoring device, to a scuba diving computer. These videos were discussed in class, and students were evaluated based on their class participation and their ability to screen the literature or relevant resources. One subject that was of particular interest was the heat exchanger. The instructor presented an educational video generated by the U.S. Chemical Safety and Hazard Investigation Board, which highlighted an accident in a chemical plant due to the failure of a heat exchanger. The case study focused on the explosion in the T2 Laboratories in Jacksonville, Florida, which killed four people and injured 32 others. The incident, which occurred on December 19, 2007, was linked to the failure of the cooling system in the runaway chemical reaction during the production of a gasoline additive. Following the discussion of this video, the students were assigned a take-home quiz to report on some of the common errors in the chemical plant which can impact public health and safety. Students reviewed the literature and generated a written report highlighting the engineer's responsibility to make informed decisions while designing solutions. The students were explicitly advised to discuss an engineer's socioeconomic, environmental, and cultural responsibilities. The students were evaluated on their ability to identify health, safety, and welfare concerns in the design of the heat exchanger equipment through the essay. Thus, the written quiz assessed the student's ability to learn and develop a rationale for safe engineering solutions.

The Transport Phenomena Laboratory course requires students to complete the SAChE Safety Training Modules on “Introduction to Managing Process Safety Hazards” (ELA953), and “Understanding Hazards and Risks” (ELA969).

The second semester (spring or summer) students complete the Reactive Process Engineering pillar. This course provides a formal introduction to Safety with one lecture focused on process safety, dealing with hazard identification, safety levels of implementation, regulatory agencies enforcing safety rules and assisting on safety evaluation, and introduces students to the paramount commitment on safety on professional ethics codes (i.e., AIChE). It also provides some basic references on safety. This lecture is accompanied by a safety assignment where students are invited to watch one of the Chemical Safety Board (CSB) videos (a list of five cases is suggested) and develop a bullet-style short report (2-3 pp.) briefly describing the incident, the causes, the prevention strategy that could have avoided the accident, and the ethical and professional responsibilities involved in the incident. They are also asked to add personal reflection and provide a personal commitment to safety.

In addition, students are required to complete a team project to research relevant issues of the production of a high-volume chemical product. They are required to address safety considerations of the production chain, including the handling of raw materials, products, and by products. The project also requires research on one major producer, including documentation on public safety records. This open-ended project to research information on product manufacturing and company performance, introducing them to a more comprehensive approach about the culture of safety, from material hazards to responsible communication with stakeholders and communities. Students gain experience from diverse sources (technical, social, business) and learn concepts and terminology of safety.

The companion lab course requires students to complete the SAChE Safety Training Modules on "Chemical Reactivity Hazards" (ELA962)

Senior year

In the fall semester of senior year, students complete the Process Control pillar. This course adds more formal content on Safety with a new lecture that revisits the concept of process safety and the culture of "Safety First," 11followed by the introduction of "safety protective layers," and specifically addresses the topics of process alarms, from design to rationalizations, and risk assessment, by fault and event tree analysis.

In addition, students must complete a special assignment on safety related to a fatal accident (T2 Laboratories Explosion) from the perspective of process control concepts and tools and developed at the University of Michigan [A7]. The assignment makes extensive use of SIMULINK to explore the temperature control of an exothermic reaction and requires teamwork in solving several activities based on the corresponding CSB video and report, and the SIMULINK model provided with the assignment. An example of the student results from this assignment is provided in Figure 1, shown below.

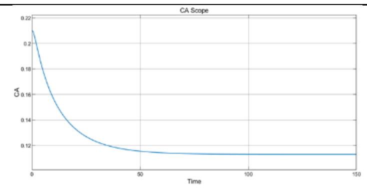
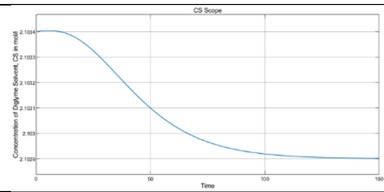
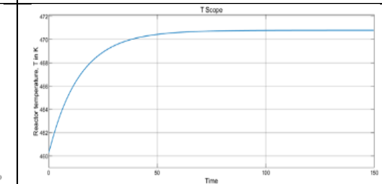
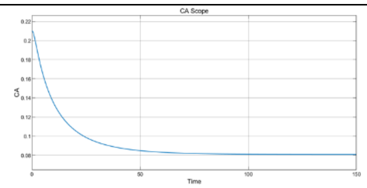
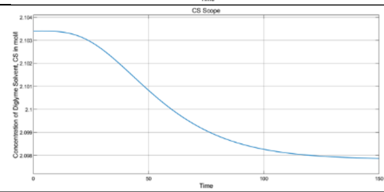
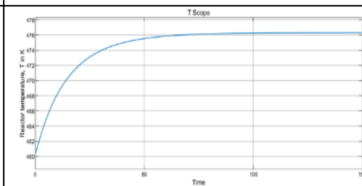
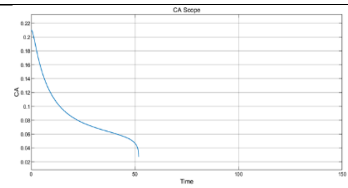
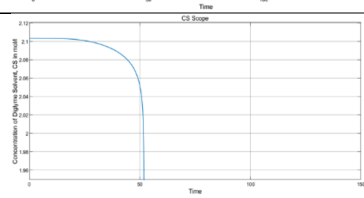
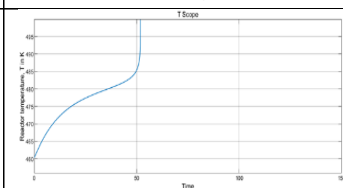
Step	*Reactant concentration*	*Solvent concentration*	*Reactor temperature*
10 K			
15 K			
20 K			

Figure 1. Reactant and solvent concentrations, and reactor temperature profiles for step size increases in feedstock temperature. Detection of the onset for the runaway reaction for the 20 K step is shown in the bottom row. [A8]

In the second semester senior year, the capstone Pillar course on Process Design integrates process safety with process synthesis, equipment design, process optimization, process economics, and social impacts for a commercial size manufacturing plant design. In one section, students focus on the design of midsize commercial plants to produce styrene (reported elsewhere [A9]); in the other section, the students select the raw materials and products that their plant will make – but otherwise complete the same design milestones. With the guidance of the instruction material in the companion course (see below), students complete the design report with a final section on health and safety addressing the safety classification of the materials involved in the manufacturing process, and their reactivity hazards, the strategies to reduce fires and explosions, some examples of Process Hazard Analysis (PHA) on selected components (i.e., storage tanks) (Table 2), selection of piping and equipment materials from safety analysis, danger and mitigation strategies, and the required use of Protective Personal Equipment (PPE). In addition, a lecture is devoted to safety in storage tanks handling flammable materials. One example illustrates the case of explosion risk at styrene storage (in a tanker truck) using a blanketing gas while required to provide a certain level of dissolved oxygen maintain the activity of the polymerization inhibitor provided in Figure 2.

Table 2. Example of PHA for the styrene storage tank at the styrene production plant [A10]

What If	Consequence	Safeguards	Recommendations
Styrene in storage tank starts to polymerize	Ruin final product and could cause vessel to rupture	Put TBC in storage tank to inhibit polymerization	Keep constant concentrations of TBC in tank and use multiple styrene tanks with lower volumes
Styrene tank runs out of styrene	Could run out of product to sell and run unloading pump dry	Automatic pump shutoff for unloading when high level is reached	Implement level sensing technology (low level alert)
Blockage to tank	Pump continues to supply heat to the styrene feed	Automatic pump shutoff when downstream flow goes below value or temperature immediately at pump outlet increases above unsafe number	Flow meter and thermocouple between the pump and the tank inlet
Styrene tank is approaching overfill	Potential for backflow into distillations columns	Automatic Pump shutoff when high level is reached and check valve to prevent backflow	Implement level sensing technology (high level alert)
Styrene tank is overfilled	Potential for backflow into distillation columns	High level tuning fork level switches at top of interior of tank	Implement level sensing technology (high level alert)
Rupture in wall/roof	Styrene evaporates from the tank into the atmosphere	Secondary lining inside of the storage tank	Regularly monitor the outside of the tank to ensure that there is no significant damage

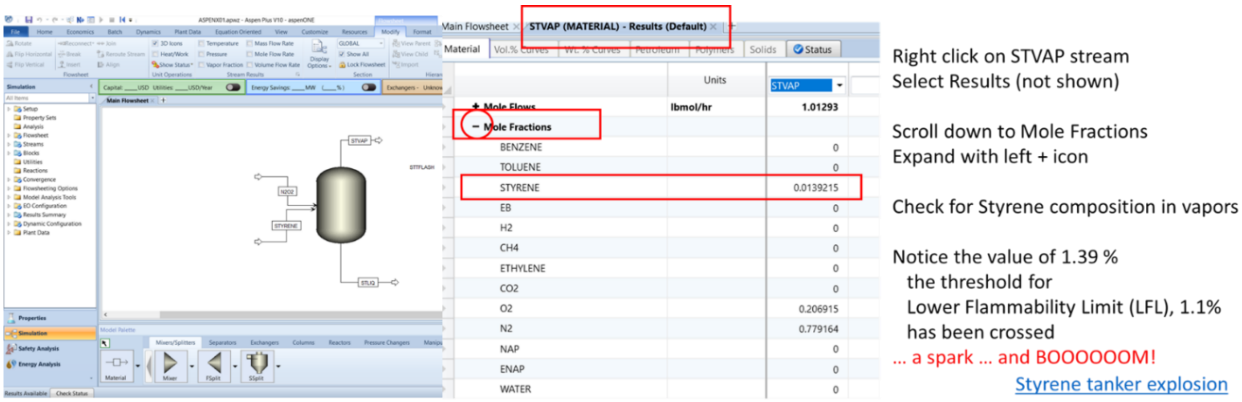


Figure 2. ASPEN simulation to assist in designing styrene storage tank to prevent explosion

The companion two-credit course on Ethics and Safety requires students to complete ten Level Two SAChE modules and one Level Three (Advanced) module. In Summer 2023, three additional Level Two SAChE courses will be added, thereby enabling all students to complete the entire SAChE Level One (Basic) and Level Two (Intermediate) curricula prior to graduation. Each of the 14 two-hour lectures starts with a ten-minute review of a Chemical Safety Board incident report and video (students have watched the associated video prior to class). These 14 investigations are carefully chosen from CSB's enormous menu of investigations to reflect a wide variety of dangerous scenarios (e.g., fires, toxic chemical releases, decomposition explosions, improper management of change, unexpected hydrate formation, liquid hammer fracturing of metal, incorrect material of construction selection). The first two lectures of the Safety and Ethics course are devoted to Professional Ethics, and the next ten lectures cover four major accidents for which the instructor served as a consultant charged with explaining the causes of each disaster. These four stories serve as interesting frameworks for explaining the main concepts of plant health and safety (no proprietary information is provided to the students). During the final two lectures, students are taught how to generate a standard operating procedure, accurately demonstrate that a piece of equipment meets the relevant standards and codes and conduct a "what-if" style HAZOP. Student teams have three projects during the course. First, they completed a report on the technical and ethics-related causes of the Deepwater Horizon catastrophe. Second, the teams analyze a fatal oilfield storage tank explosion and propose improved designs aimed at preventing future similar explosions. Third they prepare a safety chapter for their team's final report in the companion Plant Design course in which they design a piece of equipment "meets code" (ASME), conduct a HAZOP study related to the operation of one unit, compile SDS documents for all chemicals, list the appropriate PPE for plant workers, and design a pressure relief valve.

Assessment of Safety Assignments

One hundred percent of our students (~250 sophomore through senior year) have successfully completed the seven SAChE certificates (which requires at least an eighty percent on the quiz) in the CHE 101, 201, 301 and 401, as well as the EH&S Chemical Hygiene exam – as these are minimum requirements for our degree program. We have also collected assessments for the safety portion of the sophomore level hands-on design project, which has averaged 7.6/10 over the last seven years. The junior level projects have averaged 83.8 over the last several years, and the senior level process control safety assignment has averaged 85.3. And finally, in the senior level process design course, the section which focused on safety, health and welfare of the plant design, averaged 81%, over the last six years.

In the Safety & Ethics course, the students' understanding of safety was measured by their successful completion of ten Level One and Level Two SAChE modules. This accomplishment was a Direct Assessment of Outcome 7, where students were required to complete 9 of 10 assigned Level One and Level Two SAChE modules to meet the standard reflecting satisfactory acquisition and application of new knowledge. (The students did not record their actual grade on these exams, only whether or not they passed it as evidenced by their time stamped SAChE certificates for the modules). In the summer of 2022, the grades for the 16 students ranged from 50-100% completion, averaging 93%, with 3 students failing at attain the standard of 90%. In the spring of 2023, the grades for the 48 students ranged from 30-100% completion, averaging 97%. On the midterm exam there were three questions for each of five SAChE modules, totaling 15 of the 100 questions on the midterm. In the summer of 2022, the mid-term subgrade (for those 15 safety questions) for the 16 students ranged from 33 to 100%, averaging 80%. In the spring of 2023, the mid-term sub-grade for the 48 students ranged from 33-100%, averaging 71%. On the final exam, there were three questions for each of the other five SAChE modules, a total of 15 of the 100 questions on the final. In the summer of 2022, the final subgrade (for only those 15 safety questions) for the 16 students ranged from 53-100%, averaging 83%. The final exam has not taken place at the time of writing this draft but can be included in the final draft (if accepted).

Safety considerations based on class materials and SAChE module content were required to answer many questions on the Deepwater Horizon incident homework assignment. For examples, the teams had to provide technical reasons for the disaster, an assessment of the safety culture prior to the event, a review of the safety guidelines that were followed (or violated) leading up to the disaster, and an accurate descriptions of the dangers associated with the fire, explosion, and oil leak. Unfortunately, the grading rubric was not designed to extract a subgrade for the assessment of the safety considerations.

Safety considerations were also required for the Oilfield Storage Tank Explosion incident design projects. For example, the student teams had to explain the technical reasons for the disaster, provide an assessment of the safety culture in the company and community leading up to the event, review the safety guidelines and state regulations that were followed (or violated) leading up to the disaster, and give an accurate description of the dangers associated with the fire and explosion. Again, the grading rubric was not designed to extract a subgrade for the assessment of the safety considerations.

Assessment of Ethics Assignments

The students' understanding of professional ethics issues and considersations was rigorously measured in two manners and qualitatively assessed in two other methods. The ethics-related SAChE module assigned to the students, who were required to pass the Level One course "Process Safety Ethics – A Brief Introduction." They were not required to reveal their SAChE exam score, but they did have to 'pass' the SAChE exam with at least 80% correct to obtain the certificate, which they then submitte. Not surprisingly, sixteen students in summer 2022 and 48 students in Spring 2023 successfully completed this module. This accomplishment played a small part ($1/10^{th}$) of an assessment associated with Student Outcome 7, where studers were required to complete 9 of 10 assigned Level One and Level Two SAChE modules to satisfactorily demonstrate their ability to acquire and apply new knowledge.

After attend two 2-hour lectures on professional ethics given by a guest lecturer, who had a 40+ year chemical engineering career with several companies, most notabliy Lubrizol, the students took a 40 or 67 questions exam focused soley on professional ethics. The standard for this ABET direct assessment of Outcome 4 was 80%. In summer 2022, the grades for the 16 students ranged from 80 to 100 %, averaging 95%. In spring 2023, the grades for the 48 students ranged from 74-100%, averaging 89%.

Ethical considerations were required to make an informed judgement for many questions on the Deepwater Horizon incident homework assignment. For example the teams had to explain what persons/companies were responsible for the disaster, whether the use of dispersants were justified, the response of the companies involved, the decisions made to kill the well and clean up the spill, the reason for misinterpretatiaon of negative pressure test results, the lack of cement testing, the decision to limit fishing, the changes in deepwater drilling of ultradeep wells, the decisions concerning what persons/companies should have been held responsible to make financial compensation, etc. The results of this assessment of the ethical considerations will be provided at the end of this semester.

Ethical considerations were also required to make an informed judgement for questions on the Oilfield Storage Tank Explosion incident design project. For example, the student teams had to address who/which companies were responsible for the explosions, whether trespassers who purposefully or inadvertently cause an accident can still demand compensations or expect design changes to improve safety, the reasonable amount of money that can be spent to make a storage tank safe, the determination of why companies may or may not follow regulations, the appropriate level of signage, the appropriate amount of security (locks, fences, security cameras) for a remote oil collection and storage tank, the best strategy to approach the community about the hazards of the sol storage tanks. Unfortunately, the grading rubric was not designed to extract a subgrade for the assessment of the ethical considerations (the rubric will be changed in the summer of 2023 to provide an ethics subgrade.

Conclusions

Our department has integrated safety into the curriculum using a wide variety of tools coordinated across the sophomore, junior and senior years. SAChE modules are assigned in every course and lab, with an additional ten being required in the Safety and Ethics course. This enables each student to complete the Level One and Level Two SAChE curricula. CSB investigation reports and videos are used in several courses, with 14 CSB reports integrated in the Safety and Ethics course. It is our aspiration that the students will develop a life-long learning habit of regularly reviewing CSB reports and enrolling in additional Level Three SAChE modules.

Hands-on lab safety training occurs in each of our five experimental lab courses. The instructor, who had a thirty-year career in industry, includes general safety training which includes completing and passing the EH&S Chemical Hygiene training, proper laboratory safety attire, location of safety equipment and emergency measures.

Team projects associated with five of the six pillar courses not only require a rigorous technical design, but also include meaningful and relevant safety considerations. This is usually accomplished with a lecture related to safety in the classroom, followed by instructions on how to properly consider safety during the design. Assessment of student’s knowledge of safety (by means of SAChE Certificate completion, homework, quizzes, design project sections) have increase from sophomore to senior year.

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