2026 ASEE ANNUAL CONFERENCE
June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #50400

Establishing Process Safety Culture in the Chemical Engineering Curriculum

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Establishing Process Safety Culture in the Chemical Engineering Curriculum

Introduction

Beginning in 2011, the Accreditation Board for Engineering and Technology (ABET) has required chemical engineering undergraduate programs to provide students with instruction in chemical process hazards, with the current program criteria for chemical engineering programs stating that curriculum must include: “Engineering applications of these sciences (chemistry & physics) to the design, analysis, and control of processes, *including the hazards associated with these processes* (emphasis mine)” [1]. This requirement followed the 2007 incident at T2 Laboratories and the subsequent 2009 Chemical Safety Board incident report that identified a lack of process safety instruction and specifically instruction in reactive hazard recognition and management in baccalaureate chemical engineering programs [2].

Since that time, ABET accredited undergraduate chemical engineering programs have worked to meet this requirement and industry needs in a variety of ways, including offering required standalone safety courses [3], embedding process safety instruction throughout the core curriculum [4-7], and sometimes offering elective courses in process safety to give students an opportunity to enhance their education in chemical process safety beyond core requirements [8]. Chemical engineering faculty have worked to establish best practices for effectively motivating and teaching students to incorporate and value hazard recognition and analysis, especially in their laboratory and design activities. This has included industry mentorship [9,10], the use of Safety and Chemical Engineering Education (SAChE) modules [4-6,11], and digital immersive environments [12].

Chemical process safety education at The University of California, Davis (UC Davis) has evolved since the 2011 ABET mandate. Initially, process safety topics formed a substantial part of one required fourth-year process design course. Currently, process safety topics are now prevalent in three core chemical engineering undergraduate courses. These courses include a first-year “Chemical Engineering Profession” course, a fourth year “Process Economics and Green Design” course, and a fourth year “Plant Design Project” course. Completion of selected Safety and Chemical Engineering Education (SAChE) modules are required of all students in their third and fourth years. Finally, a recently developed “Chemical Process Safety Fundamentals” course is offered as an elective to third and fourth-year students in the program. Inclusion of process safety topics across multiple courses has allowed the program to better draw connections between process safety topics and skill sets developed in other core coursework including thermodynamics, transport phenomena, reaction kinetics, and control. Additionally, process safety topics allow students opportunities to practice professional and ethical analysis and decision-making skills.

This paper will detail the integration of process safety topics in the chemical engineering curriculum at UC Davis. The program aims to foster a culture of process safety [13] among the students by establishing process safety as a core value, cultivating a sense of vulnerability, and teaching students how to communicate about safety.

Establishing Safety Culture through Process Safety Education in the Undergraduate Chemical Engineering Curriculum

First Year Chemical Engineering Profession Course

To establish process safety as a core value in the chemical engineering curriculum at UC Davis, process safety instruction begins in the first year "Chemical Engineering Profession" course. This is a 1-unit required course that meets one time per week during the first (Fall) term and is targeted towards students entering the chemical engineering program as first-year or transfer students at UC Davis.

The stated purpose of this course is to help students develop an awareness of the role of chemical and biochemical engineers in society. Students are to become familiar with the breadth of potential careers in (bio)chemical engineering, and the professional and ethical responsibilities associated with those careers. Learning activities include readings on contemporary issues taken from AIChE's *Chemical Engineering Progress* magazine, topical lectures on issues such as carbon sequestration & utilization, biotechnology, and use of AI, lectures on chemical engineering ethics & professionalism (detailed more below), discussion on these issues in-class and on discussion boards, and guest presentations from practicing chemical engineers. Course assignments include participation on class discussion boards, drafting a professional resume, and writing two major essays. Through the course learning activities and assignments, students are given the opportunity to develop an appreciation of the need for life-long learning and the tools for such learning.

Engineering ethics and professionalism is a major component of this course, accounting for about 30% of the course learning activities. It is through this lens that students are first exposed to important chemical process safety incidents selected for their historical and regional significance. Class reading and discussion begins with the Bhopal incident, which helps to foster a sense of vulnerability among the students due to the catastrophic loss of life. Students view Chemical Safety Board videos for the Chevron Richmond Refinery [14], a local incident, and Deepwater Horizon [15], which demonstrate risk management failures and the need for safety culture. During class time, the instructor and students discuss safeguards that were in place, which failed and why, and the failure of ethical and/or professional responsibilities in these scenarios. Class discussion also includes an introductory-level presentation of inherently safer design principles and how they apply to these incidents.

After these learning activities, students begin to practice communicating about safety by completing an assignment (essay) where they research and analyze a process safety incident not discussed in class. Students are directed to the repository of Chemical Safety Board videos from which they can choose an incident to study. In their essay, students are required to:

- Summarize the incident (must be related to chemical processing)
- Identify and discuss safeguards that were in place and which safeguards failed in this scenario
- Present their opinion on what should have been done to prevent the incident from occurring
- Identify the applicable parts of the AIChE Code of Ethics [16] and which, if any, were violated in this incident

At the conclusion of this introductory course, students are familiar with at least four chemical processing incidents (Bhopal, Deepwater Horizon, Chevron Richmond Refinery 2012, and an incident of their choosing), what safeguards are and examples of types of safeguards, inherently safer design, and how the professional responsibility of chemical engineers includes "holding paramount the safety, health, and welfare of employees and the public" [16]. In addition to the establishing a sense of vulnerability, by including this material in this introductory course, chemical process safety is established as a core value in the chemical engineering undergraduate curriculum.

Use of SAChE Modules

Further on in the curriculum, in upper division laboratory and design-oriented courses, students complete a short series of Safety and Chemical Engineering Education (SAChE) modules available free to undergraduate students through the free national American Institute for Chemical Engineers (AIChE) student membership. In a third year "Thermodynamics Laboratory" course, students complete the "Lab Safety" SACHE module in preparation for their three major-specific laboratory experiences [17]. In a fourth year "Process Economics and Green Design" course, students complete a process safety unit, detailed in the subsection below. An additional requirement of this course is that students complete three SACHE modules, "Hazards and Risk: Introduction to Hazard Identification and Risk Analysis" [18], "Inherently Safer Design" [19], and "Risk Review Using LOPA (Layer of Protection Analysis" [20].

These modules give students additional exposure and reinforcement to safety concepts learned in class, as well as course certificates that they can include on their resumes. Including SACHE modules, which broaden students' safety education outside of their institutional experience, reinforces process safety as a core value in these courses and in the curriculum and additionally gives students additional tools for the documentation and evaluation of safety hazards.

Process Economics and Green Design Course

The Process Economics and Green Design course at UC Davis is intended to introduce students to the fundamentals of chemical process design, process safety, process simulation, and process economics. Students work in teams on several small design activities that are geared towards preparing them for their capstone design project. The process safety unit of the course consists of three of the seventeen course lectures, three in-class activities, one out-of-class group design assignment, and incorporation into a future design assignment as well as the final exam.

In this unit, students are introduced to toxic hazards, industrial health & hygiene hazards, fire & explosion hazards, and reactive chemical hazards. These topics continue to cultivate students' sense of vulnerability. Chemical Safety Board videos continue to be utilized to illustrate related incidents. The case studies used in this course include BP Texas City, 2005 to illustrate a lack of process safety culture [21], The Danger of Popcorn Polymer: Incident at the TPC Group Chemical Plant, 2019 to illustrate reactive chemical hazards [22], and Ethylene Release and Fire at Kuraray America in Pasadena, Texas, 2018 to illustrate pressure relief and associated design failures [23].

Student also learn risk identification and analysis using HAZOP (Hazard & Operability Studies), giving the students a method for hazard documentation and evaluation. Students are also taught inherently safer design principles, engineering controls and safeguards, and the basics of LOPA (Layer of Protection Analysis).

At the end of this unit, for the associated out-of-class design assignment, students conduct a constrained HAZOP around an assigned unit operation and report out on potential hazards, and how they recommend mitigating these hazards. This gives students practice in identifying, documenting, and evaluating hazards and communicating about these hazards, their potential severity, and ways to mitigate them. In a future out-of-class design assignment for this course, student groups are tasked with beginning research into their capstone design project topic. As a part of this assignment, the teams are required to identify significant safety or biological hazards that they can anticipate at this time. Final exam questions typically assess students' knowledge of key vocabulary (e.g. risk, safeguards, etc.), HAZOP structure and guidewords, preventative vs. mitigating safeguards, and inherently safer design.

Plant Design Project (Capstone) Course

In this capstone design course, instructors make connections between safety concepts learned in previous coursework and applications in students' capstone design projects. Because these projects require the students' original approach to solving their assigned design problem, students have the opportunity to practice the cultural value of leadership as it relates to integrating safety into their designs. By previously establishing safety as a core value and cultivating a sense of vulnerability in relation to processing hazards, students are now in a position apply learned documentation and evaluation practices and communicate about safety in an effective way. Finally, since this course revolves around the group capstone projects, students also have the opportunity to cultivate the value of mutual trust in developing their designs, safety evaluations, and group products.

One of the capstone project progress reports, assigned towards the middle of the process development phase, requires students to report on how inherently safer design principles have been incorporated into their designs, and their approach to prevent and mitigate major potential safety hazards. This exercise is intended to ensure that groups are evaluating risks and considering inherently safer solutions during the course of their design work and not as an afterthought when they are carrying out their final design assessments. Students receive feedback from their faculty design instructor on this progress report and are able to incorporate feedback into their designs.

Later in the course, near the completion of their design work, students are tasked with performing a HAZOP around a unit operation assigned by their faculty design instructor (usually what the instructor considers to be the most hazardous unit operation in the process). Similar to the assignment in the "Process Economics and Green Design" course, in addition to the HAZOP analysis, students must also write a summary statement of the most significant hazards associated with this unit operation and their proposed strategies for mitigating these hazards.

Finally, 10% of the grade on students' final design reports is allocated to the students' holistic consideration of health & safety concerns and risk considerations. Specifically, students are required to identify significant, specific health & safety concerns and define mitigation strategies. They are required to include relevant lessons learned from the industry and how those lessons have been incorporated into their design. Finally, these are required to report on how inherently safer design principles have been incorporated into their designs.

Chemical Process Safety Fundamentals Elective Course

Finally, students in the chemical engineering program at UC Davis can choose to enhance their process safety education by enrolling in an elective course entitled "Chemical Process Safety Fundamentals." A significant percentage (about 50%) of students in the chemical engineering major at UC Davis have taken advantage of this elective course over the past two offerings.

This course offers students in-depth coverage of process safety topics beyond what is covered in the core courses including hazard identification and evaluation, risk analysis and assessment, toxicology, fire & explosion hazards, and reactive chemical hazards. Additionally, students learn how to derive and use source and dispersion models. This course makes use of the Crowl & Louvar "Chemical Process Safety: Fundamentals with Applications" textbook [24]. The course follows and heavily references the "Process Safety Knowledge framework" [25], challenging students to consider:

- What are the hazards and how are they characterized?
- How can the hazards be eliminated and controlled?
- What can go wrong and how?
- What are the consequences?
- What is the likelihood?
- What is the risk and is it acceptable?

This course makes heavy use of Chemical Safety Board videos to foster discussion around these questions and illustrate course topics. Specific case studies and the topic they relate to are listed in Table 1.

Table 1. Selected Case Studies and Associated Topics in the Chemical Process Safety Fundamentals Elective Course.

Topic	Case Study	Source
Introduction	Piper Alpha	[26]
Toxicology	Toxic release at DuPont LaPorte Facility	[27]
Industrial Health and Hygeine	Hydrogen sulfide release in Odessa, TX	[28]
Reactive chemical hazards	Runaway rxn at T2 labs (reactive chemical hazards)	[29]
Source models	DuPont Bell, WV leaks	[30]
Fire and explosion hazards	Flixbourough	[31]
Fire and explosion hazards	PCA Louisiana pulp and paper mill	[32]
Static electricity	Barton Solvents, KS	[33]

Students in this course are assessed using four out-of-class project-type assignments (25% of grade), four quizzes (30% of grade), a culminating group project (20% of grade), and a final exam (25% of grade). The out-of-class project-type assignments require the following:

- Situational analysis, hazard identification, chemical properties, toxicological information, exposure limits, inherently safer solutions, and how to communicate to the public about hazards.
- Reactive chemical hazards and required preventative and mitigating safeguards
- Source model derivation and calculation of maximum rate of release and tank emptying time.
- Incident model using ioMosaic's SuperChems™ software.

For the final group project, students are provided with a process flow diagram and results from a completed process simulation and are tasked with making an oral presentation on the key hazards, risks, consequences, and mitigation strategies. The assessment processes that students are required to use to generate the content for their analyses and reports are HAZOP and LOPA.

Assessment

Methods

Assessment data is collected in each of these courses to track student achievement of process safety related student outcomes. Two assessments in particular are used to help assess ABET student outcome 4, which is "an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts" [1]. Our program has defined three performance indicators for ABET student outcome 4:

1. Demonstrates working knowledge of the AIChE Code of Ethics by recognizing appropriate/key ethical dilemmas,
2. Recognizes the important global, economic, environmental, and social issues involved in an engineering solution, and
3. Makes informed judgements based on the evaluation of alternative engineering solutions or scenarios, taking into consideration relevant conflicting/competing social values and ethical issues as well as important global, economic, environmental, and social issues.

One of the assignments used in this assessment is the "Analysis of a Process Safety Incident" essay administered in the first-year "Chemical Engineering Profession" course (described in the previous section). One of the assignment performance indicators ("An identification of the parts of the AIChE Code of Ethics that were applicable and perhaps violated") is mapped to the first performance indicator for ABET student outcome 4.

A second assessment of ABET student outcome 4 comes from the "Plant Design Project" course, where students report of their holistic consideration of health & safety concerns and risk considerations in their capstone design projects on their final design reports (described in more detail in the previous section). Each of the three performance indicators for ABET student outcome 4 are evaluated in this assignment.

Results are presented in the following subsection for these process safety related ABET assessments as well as other key process safety assignments. Following the ABET continuous improvement process, assessment data is not aggregated but tracked on a year-by-year basis to identify cohort-specific differences in performance which are then used as a basis for curricular discussions and modification decisions. In this paper, two years of data are presented representing the most current data available to the author. Table 2 defines the cohorts presented for each course.

Table 2. Student Cohorts for Which Assessment Data are Presented.

Course	Cohorts (Academic Year)	Terms Course was Taken
"Chemical Engineering Profession"	'24-'25 (N = 108) and '25-'26 (N = 116)	Fall 2024 and Fall 2025
"Process Economics and Green Design"	'23-'24 (N = 60) and '24-'25 (N = 77)	Winter 2025 and Fall 2025
"Plant Design Project"	'22-'23 (N = 6 teams) and '23-'24 (N = 12 teams)	Spring 2023 and Spring 2024

Students taking the "Process Economics and Green Design" and "Plant Design" courses are students in their fourth or final year in the program. Fourth-year students in the '22-23 cohort spent four academic quarters under emergency remote instruction due to the COVID-19 pandemic (Spring 2020, Fall 2020, Winter 2021, and Spring 2021). Fourth-year students in the '23-'24 cohort spent their first year (3 academic quarters) under emergency remote instruction (Fall 2020 – Spring 2021), which would have nominally included taking the "Chemical Engineering Profession" course. These impacts are considered when interpreting the results of this assessment data.

Results

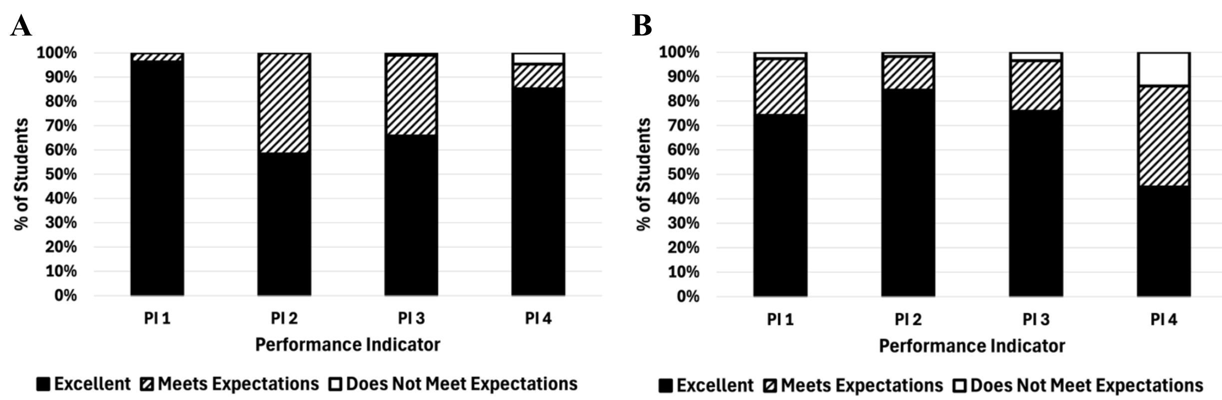

Figure 1. Student Performance on "Analysis of a Process Safety Incident" Essay in First-Year "Chemical Engineering Profession" Course. Figure 1A contains data from the '24-'25 cohort (N = 108) and Figure 1B contains data from the '25-'26 cohort (N = 116). Performance indicators for the assignment were as follows: PI 1 = "A well-presented summary of the incident", PI 2 = "A discussion of the safeguards that were in place to protect against the incident and how they failed", PI 3 = "A discussion of what you think should have been done to protect against the incident", and PI 4 = "An identification of the parts of the AIChE Code of Ethics that were applicable and perhaps violated."

Figure 1 shows two years of student performance data on the “Analysis of a Process Safety Incident” assignment administered in the “Chemical Engineering Profession” course. The fourth performance indicator on this assignment, “An identification of the parts of the AIChE Code of Ethics that were applicable and perhaps violated” is mapped to the first performance indicator for ABET student outcome 4, “Demonstrates working knowledge of the AIChE Code of Ethics by recognizing appropriate/key ethical dilemmas.”

Greater than 95% of students in the ’24-‘25 cohort were judged to have at minimum met expectations with respect to each of the four assignment performance indicators, while greater than 95% of students in the ’25-‘26 cohort were judged to have at minimum met expectations with respect to assignment performance indicators 1-3. Performance of the ’25-‘26 cohort on the assignment performance indicator 4 was significantly different than the Fall ’24-‘25 cohort, with 86.2% of students meeting expectations or receiving an “excellent” ($p < 0.025$). The reason for this discrepancy is not clear, and this outcome will continue to be monitored by the program. As previously stated, this 4th assignment performance indicator is used in the ABET student outcome 4 assessment.

Table 3 shows two years of student performance data in the “Plant Design Project” course from the component of final capstone design reports that deals with holistic consideration of health & safety concerns and risk considerations. In these two years, each student design team was judged to have at minimum met expectations on this aspect of their final design report.

Table 3. Student Performance on Safety Component of Final Design Project Reports in Fourth-Year “Plant Design Project” Course.

	’22-23 Cohort*	’23-24 Cohort
% of Excellent Ratings	16.67%	33.33%
% of Meets Expectations Ratings	83.33%	66.67%
% of Does Not Meet Expectations Ratings	0%	0%

* Data from ’22-‘23 cohort reflect performance of one section of the “Plant Design Project” course, or 6/16 design teams.

In order to map this assessment to ABET student outcome 4, design instructors conduct a separate evaluation of each of the three performance indicators (independent of student grades on the assignment.) For the ’23-‘24 cohort, each of the 12 student design teams that year were judged to have met or exceeded expectations with respect to performance indicators 1 and 3, and 11/12 design teams (91.7%) were judged to have met or exceeded expectations with respect to performance indicator 2 (“recognizes the important global, economic, environmental, and social issues involved in an engineering solution”).

Prior to being held responsible for process safety considerations on their final design reports, students complete several process safety-related assignments in the three safety-associated core chemical engineering courses. As described previously, students in “Process Economics and Green Design” are required to complete three SAChE modules. 95.1% of the ’23-‘24 cohort successfully completed all three SAChE modules, with 98.4% of students completing 2/3 required modules. 93.6% of the ’24-‘25 cohort successfully completed all three SAChE modules, with 98.7% of students completing 2/3 required modules.

Students in the “Process Economics and Green Design” course conduct a constrained HAZOP around an assigned unit operation and report out on potential hazards, and how they recommend mitigating these hazards (described in more detail in the previous section). Figure 2 shows two years of student performance data on this assignment.

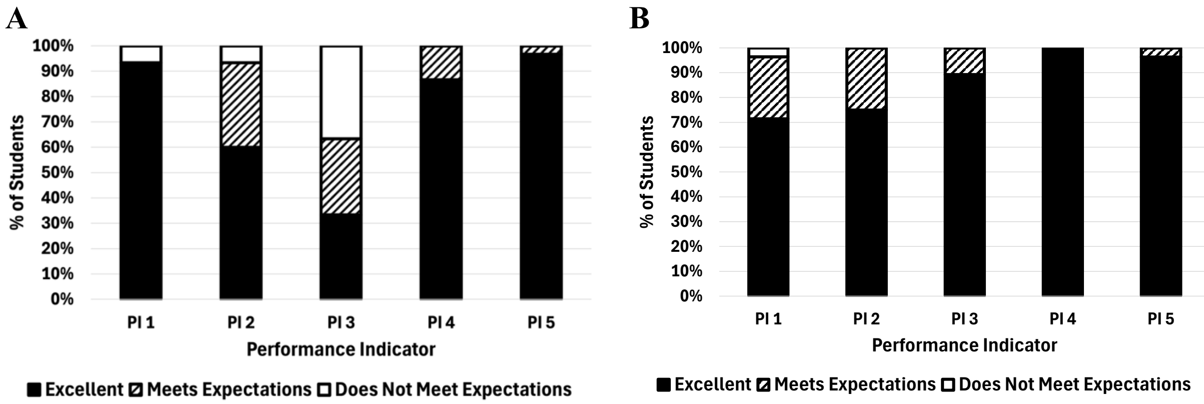

Figure 2. Student Performance on HAZOP Assignment in Fourth-Year “Process Economics and Green Design” Course. Figure 1A contains data from the ’23-‘24 cohort (N = 60) and Figure 1B contains data from the ’24-‘25 cohort (N = 77). Performance indicators for the assignment were as follows: PI 1 = “Important events resulting from potential deviations from standard operating conditions were identified and appropriate guide words were chosen to describe these events”, PI 2 = “Reasonable and appropriate potential cause or causes for each deviation was identified”, PI 3 = “Reasonable and appropriate consequences of identified deviations are discussed and appropriate actions to be taken are noted and reasonable”, PI 4 = “Summary of findings identifies potential major incidents”, and PI 5 = “Summary of findings suggests safeguards or actions to be taken that could be used to reduce the likelihood of or help mitigate potential disasters.”

Greater than 93% of students in the ’23-‘24 cohort were judged to have at minimum met expectations with respect to assignment performance indicators 1, 2, 4, and 5, and greater than 95% of students in the ’24-‘25 cohort were judged to have at minimum met expectations with respect to each of the assignment performance indicators 1-5. There was a significant difference between the two cohorts with respect to achievement on assignment performance indicator 3 (“reasonable and appropriate consequences of identified deviations are discussed and appropriate actions to be taken are noted and reasonable”), with only 66.33% of students in the 2024 cohort meeting or exceeding expectations ($p < 0.01$).

This discrepancy was also seen in the same “Process Economics and Green Design” course on a final exam question that assessed students’ knowledge of HAZOP key words, preventative and mitigating safeguards, and inherently safer design. As shown in Table 4, students in the ’24-‘25 cohort fared much better on this identical final exam question. This difference in performance between the two cohorts is statistically significant ($p < 0.01$).

Table 4. Student Performance on Safety Question on Final Exam in Fourth-Year “Process Economics and Green Design” Course (score out of 13 points).

	’23-‘24 Cohort (N = 60)	’24-‘25 Cohort (N = 77)
Average Score	8.35 (64.2%)	11 (84.6%)
% of Students Scoring at least 10/13	36.67%	84.4%
% of Students Scoring at least 7/13	75%	96.1%

Anecdotally, this discrepancy is consistent with performance discrepancies seen between these two cohorts on other assignments in this and other courses. The majority of the ’23-‘24 cohort at UC Davis spent their first year (Fall 2020 – Spiring 2021) under emergency remote instruction due to the COVID-19 pandemic. This cohort was smaller than previous and subsequent cohorts (N = 60 compared to N = 77 for the ’24-‘25 cohort) and the difference in performance may reflect a combination of preparation issues and a loss of students from that class to other institutions or to delayed enrollment.

The ’24-‘25 cohort also had the benefit of an additional midterm exam with two safety related questions that had the potential to prepare students better for the final exam. These questions also assessed students’ knowledge of HAZOP key words, preventative and mitigating safeguards, and inherently safer design. Student performance on these questions is shown in Table 5.

Table 5. ’24-‘25 Cohort Performance on Safety-Related Midterm Exam Questions in Fourth-Year “Process Economics and Green Design” Course.

	HAZOP Question	Safeguards & ISD Question
Average Score	5.64/8 (70.5%)	15.9/18 (88.3%)
% of Students Scoring at least 75% on question	65.4%	83.3%

One other set of safety-related assessments occur in the "Plant Design Project" course, where, prior to being held accountable for their holistic consideration of hazards and process safety on their final design reports, student groups complete two process safety related progress reports and deliver one major midterm oral presentation with a required safety component. Tables 6 and 7 show two years of student performance on these assignments. Taken collectively, students are demonstrating that they have a working knowledge of these concepts and prepared to apply them in the context of their capstone design projects.

Table 6. Student Performance on Safety-Related Progress Reports in Fourth-Year "Plant Design Project" Course.

	'22-'23 Cohort*	'23-'24 Cohort
Inherently Safer Design Report: Average Score	93%	89%
HAZOP Report: Average Score	91%	90%

* Data from '22-'23 cohort reflect performance of one section of the "Plant Design Project" course, or 6/16 design teams.

Table 7. Student Performance on Safety Component of Midterm Oral Presentation in Fourth-Year "Plant Design Project" Course.

	'22-'23 Cohort*	'23-'24 Cohort
% of Excellent Ratings	66.67%	16.67%
% of Meets Expectations Ratings	33.33%	83.33%
% of Does Not Meet Expectations Ratings	0%	0%

* Data from '22-'23 cohort reflect performance of one section of the "Plant Design Project" course, or 6/16 design teams.

Conclusion

In conclusion, by integrating process safety instruction into three core undergraduate chemical engineering courses and by offering students the opportunity to extend their knowledge through a dedicated elective course, the chemical engineering program at UC Davis has been successful in establishing process safety as a core value, cultivating a sense of vulnerability, and teaching students how to communicate about safety. This is evidenced by assessment data confirming that most students are achieving ABET and other assignment-specific safety-related learning outcomes. This success can be attributed in large part to the integration of safety topics into multiple courses, with some courses having a significant safety component and others making use of one module (e.g. the SAChE "Lab Safety" module in the "Thermodynamics Laboratory" course). To establish safety culture in undergraduate chemical engineering programs, it is recommended that programs look for opportunities to integrate safety topics into multiple required courses, even if is just one Chemical Safety Board video or one SAChE module. This helps to demonstrate the importance of these topics and to keep safety a current and relevant concern for students. With the field of process safety and the chemical engineering profession ever evolving, the program will continue to modify and enhance process safety instruction in the undergraduate curriculum to meet accreditation requirements and industry needs.

Acknowledgements

Process safety was not an area I had much exposure to when I began my faculty appointment and teaching assignments in 2015. I am very grateful to my mentors and the professional development opportunities I had that informed my cultivation and integration of process safety education into our chemical engineering curriculum at UC Davis. Thank you to Dr. Ahmet Palazoglu (UC Davis), my co-instructor and mentor in teaching process design during my early teaching years. Thank you to Ms. Anne O'Neal (Chevron) who has volunteered to guest lecture and share her expertise in process safety with our senior chemical engineering students, and who inspired me to do more. Thank you to Mr. Andreas Towarnicky (formerly at Marathan, now at University of Pittsburgh) for your years of teaching & mentoring our senior design students, helping us offer relevant quality capstone design experiences for our students, helping to expand the safety component of our design projects, and for offering the first iteration of our chemical process safety elective course. Finally, I'd like to thank the organizers of the CCPS Process Safety Bootcamp, which I was incredibly fortunate to attend in 2016 at the Chevron Richmond Refinery. This was truly a seminal experience early in my career and it has shaped a large part of my instruction since then.

Table of Acronyms and Abbreviations

Acronym/Abbreviation	*Definition*
ABET	Accreditation Board for Engineering and Technology
AI	Artificial Intelligence
AIChE	American Institute of Chemical Engineers
CCPS	Center for Chemical Process Safety
CSB	Chemical Safety Board
HAZOP	Hazard and Operability Study
LOPA	Layer of Protection Analysis
PI	Performance Indicator
SAChE	Safety and Chemical Engineering Education

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