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Project-Based Learning and Industry Collaborations to Integrate Process Safety in an Undergraduate Chemical Engineering Laboratory

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INTRODUCTION

Process safety education is a key aspect of a chemical engineer's training that focuses on identifying hazards, managing risks, and preventing accidents [1]–[3]. The practice of laboratory and process safety in engineering courses offers multiple educational benefits and opportunities to help the professional development of students[2], [4], [5]: (1) it introduces students to the application of their chemical engineering knowledge to real-life situations, (2) it requires students to solve complex problems at the intersection of engineering and management, and (3) it fosters collaboration and trust building amongst team members. By the practice of safety, students gain valuable analytical, managerial, and leadership skills that will be key in their post-graduation careers and that will help facilitate their transition to the workforce.

It has been reported that chemical engineering programs utilize different and inconsistent approaches to integrate process safety education into their curriculum [1], [2], [6]–[9]: some programs offer a required or elective process safety course, others incorporate external online training within core chemical engineering courses (e.g., the AIChE Safety and Chemical Engineering Education (SACHE) certificate program), and a third common approach has been including chemical process safety education into laboratory or design courses. However, regardless of the preferred approach, few studies have detailed the use of hands-on experimental experiences to teach the practice of process safety in engineering at the undergraduate level [3], [10]. We have previously reported on the utilization of problem-based learning (PBL) and project-based learning (PjBL) tools in our undergraduate chemical engineering laboratories to promote self-directed learning and contribute to the formation of skills required by the modern engineering work environment [11]. In this study, we expand on the use of our laboratories, class projects, and PjBL to enhance the awareness and perception of safety in chemical engineering students. This has been accomplished by the creation of a safety sequence, the incorporation of an independent class project that integrates safety practices, and a focus on safety collaborations with our industry partners.

Project-based learning is typically defined as a pedagogical approach that engages students in the learning process through meaningful projects and the development of products created from these projects [12]–[14]. PjBL centers on the construction of knowledge by challenging students to solve complex problems. PjBL offers new learning opportunities as students collaborate to conduct research, integrate theory, formulate solutions, complete projects, and generate research products [12], [13], [15]. In our case, we have capitalized on our recently renovated laboratory sequence to effectively integrate the practice of safety in our undergraduate chemical engineering laboratories. We have utilized the PjBL framework as a tool to magnify safety learning.

A second element of our approach to teaching safety has been on fomenting and expanding our collaborations with industry partners and department alumni. Through this focus, we emphasize industry and alumni collaborations to enhance process safety education, and we prioritize the effective use of guest lectures and the creation of project safety meetings to foment a culture of safety in our students [16]–[18] (i.e., one-on-one discussions with industry professionals to discuss laboratory safety, process safety, and process scale-up).

Our industry partners have been active at helping us in our safety efforts: they tour our laboratories, they participate in guest lectures to discuss process safety, they help us improve safety in our laboratory experiments, they help enhance our safety initiatives, and they dedicate time and resources to discuss process safety with our students. We are also committed to learning from their expertise as we dynamically improve our courses, add practical elements that encourage a renovated safety culture, and share their objective in making safety a priority for recent chemical engineering graduates.

This manuscript provides an overview of the safety training implementation in our undergraduate laboratory sequence. We outline how the laboratories have been structured to gradually introduce students to the practice of laboratory safety and process safety. We also detail the positive impacts of this approach by presenting survey data on student perception of the overall laboratory safety experience, detailing the benefits of the one-on-one meetings with industry professionals, and describing the enhanced appreciation and awareness of safety by our students as a consequence of these efforts.

RESEARCH QUESTIONS

Our motivation for this research comes from our interest in providing our students with practical elements that help their transition to the professional practice of chemical engineering. Our objective is to answer the following research questions:

- Can we enhance the awareness and appreciation of safety in chemical engineering students by incorporating practical safety experiences in the undergraduate chemical engineering laboratory?
- Can the overall perception of safety as a priority to the chemical engineering profession by improved by introducing student to safety practices in the undergraduate chemical engineering program?

By this research, we pursue the creation of a renovated culture of safety in our students. In the following sections, we detail our safety sequence, the incorporation of a project-based learning (PjBL), and our industry collaborations to introduce students more effectively to the practice of process safety in our laboratories.

IMPLEMENTATION

The chemical engineering program at the University of Texas at Austin requires all degree seeking students to complete two chemical engineering laboratory courses before graduation: the Measurement, Control, and Data Analysis Laboratory in the junior year (CHE253M, 2 credit hour, referred as the “junior year laboratory”) and the Chemical Engineering Process and Projects Laboratory in the senior year (CHE264, 2 credit hour, referred as the “senior year laboratory.”) Registration in each of the courses can fluctuate slightly every term; nonetheless, it is approximately 60 to 90 students per course every semester. The courses are offered twice a year, further details on course structure and assignments have been detailed elsewhere [11].

The safety training detailed in this study was integrated in a structured manner to pursue the gradual introduction of students to the practice of laboratory safety and process safety. We selected these laboratory courses to implement the practice of safety because the format of the courses facilitates the addition of practical hands-on safety experiences; in addition, the courses include a design component that requires students to experiment and scale up processes. Below, we describe the courses and the implementation of the practical safety aspects.

Junior Year Laboratory

The junior year laboratory is the first required chemical engineering laboratory course offered in our program. This laboratory introduces students to the practice of chemical engineering through measurements, data analysis, and comprehensive reports. This course is also the first chemical engineering class to discuss the practice of laboratory safety and to emphasize relevant concepts related to process safety.

During the first week of classes all students complete online and in person training that introduces them to both lab safety and process safety. We utilize a portion of our intro lecture to explain the importance of safety in chemical engineering and its relevance to the chemical engineering industry. We also share data to support this relevance and we facilitate team discussions to help students think about possible applications of safety in their postgraduation careers. In particular, we emphasize the following:

- Safety is a priority, not a hurdle to get your work started.
- Working safely will help protect yourself and your peers.
- Being aware of safety will improve your overall engineering skills (e.g., critical thinking, management, leadership, quantitative analysis, etc.).
- Safety is a great tool to demonstrate the application of your engineering knowledge outside the classroom.
- Safety is a valuable skill that can improve your hiring profile and make you a better candidate for any engineering position.

As in other institutions, students complete safety training required by the Environmental Health and Safety department during the first week of classes (i.e., university required safety training). These courses detail the basic principles of lab safety, basic safety rules, safety contacts, and actions to take in case of emergency. Students also complete two SACHE AIChE safety training modules: ELA950 and ELA954 [19]. As described by AICHE [19], ELA950 introduces students to process safety and provides them with a basic understanding of fundamental concepts and their application in real world problems. ELA 954 reinforces laboratory safety concepts presented in our EHS training modules and prepares students to work in chemical engineering laboratories.

To introduce students to the practice of laboratory safety, we required each student to work individually and in teams in the development of three safety assignment for each of the four laboratories completed in the semester:

1. Teams create a safety section which is submitted in written format and presented to the instructors before performing each laboratory (i.e., prelab work). To complete this section, students need to think about the safety issues to be considered when carrying out the laboratory procedure. Teams determine how each experiment has some unique and important safety issues, and how there will be some safety issues that are common to all experiments. This section requires teams to discuss all precautions necessary to safeguard equipment and personnel in the laboratory. Teams must include toxicology, hazards, first aid and emergency procedures, and PPE required in the completion of the experiment. They also obtain Safety Data Sheets (SDSs) for all chemicals being used. The oral presentation of this section often leads to a safety discussion with the teaching assistant.

2. Teams perform the experiments in the laboratory. Teaching assistants have a brief discussion with students about possible safety hazards in the laboratory experiment and actions to take in case of emergency. Students follow the safety rules outlined by their prelab work and the teaching assistant oversees their experimental procedures and evaluates their safety performance.

3. In their final report, completed individually, students report and state at least 3 main safety concerns/potential hazards they discovered when performing the laboratory. Students expand and refine their prelab safety work, explain potential consequences of the identified safety concerns, and detail safeguards used in lab during the experimental procedure completion.

We believe that by completing these safety tasks students are able to recognize the importance of laboratory safety and its applications to chemical engineering, and they are able to identify possible hazards in experimental systems. In addition, this is their first opportunity to apply their chemical engineering knowledge in the solution of safety related problems.

Senior Year Laboratory

After students have been introduced to the application of laboratory safety and to basic process safety concepts in the junior laboratory, we switch our focus to process safety in the Senior year laboratory. The senior year laboratory is divided into two interdependent sections: (a) students complete four pilot-plant-type laboratory experiments, and (b) they simultaneously develop a research project that is self-directed to promote PjBL.

The first half of the senior year laboratory is focused on open-ended problems, and it is structured using elements that gradually contribute to independent learning towards PjBL. This gradual approach is also applied to the safety experience. During this half, students complete four experiments, we follow a safety format that mimics the safety practices in the junior year: students create a written safety section for each report and this prelab safety work is also presented to the instructors before each lab. In addition, each experiment requires students to solve a challenging design problem utilizing data they have gathered in the assigned experimental unit. We require each design and solution to also detail possible safety implications. Furthermore, to ensure students take a leadership role, one student in each team during each laboratory week is assigned as safety officer. The safety officer is expected to research and understand all safety precautions necessary for the experiment and laboratory. The safety officer also presents the safety section of the prelab and works on the safety sections of all necessary reports. At the completion of each experiment, each student is evaluated on their safety roles and performance in the laboratory.

The second half of the junior year laboratory focuses on the completion of proposals and self-designed experimental projects. Class projects are completed throughout the semester, we use these projects to incorporate project-based learning to the safety experience. During the first week of classes, students learn about possible experimental equipment, variables to study, and other important aspects of the projects. Thereafter, students decide on a project topic/experiment and submit their top preferences to the instructors. Students are then assigned to an experiment and each student completes a project preproposal. Even though at this point a safety section is not required (i.e., no experiments are planned yet), students are evaluated by the feasibility of their project. This feasibility includes considering resources and equipment available and explaining how their proposed idea will be completed safely in the laboratory.

The next step in the completion of the class project is the submission of a group written proposal in which each team defines the problem to be solved, the relevance of the problem, their proposed solution and approach, a summary of relevant theory and methods, their management plan, a detail of supplies and equipment needed, and a draft of the calculations needed to complete the problem solution. Teams are also required to designate a safety officer for their team, this is the student responsible for all the safety aspects of the class project. During this stage, teams follow an approach that mimics the completion of the course experiments, they develop a safety section including a summary of all safety precautions and rules/policies to follow, they also include a detail of emergency procedures, personal protective equipment required and available in the lab, and a list of common lab hazards. This safety section includes SDS for all chemicals and the final submission is signed by all team members as an agreement to follow the safety rules created by the team. Additionally, teams must identify and detail one main safety concern in their proposed research and their mitigation strategy. One week later, teams complete an oral presentation of their written proposal, during this presentation the team discusses experimental plans, feasibility of the proposed research, and safety aspects to ensure a safe working environment in the laboratory.

We also dedicate one full lecture to discuss the safety aspects of the class projects. During this lecture students are assigned to complete one AICHE SACHE course (ELA 970) to prepare for the next stages of safety in the class projects and ensure all students have a basic understanding of process safety management. It is important to note that we typically have different levels of safety knowledge in the senior laboratory: about 75% of students have taken an optional chemical process safety course in our department (CHE364S – Chemical Process Safety), and a high percentage of students have had internships or have completed undergraduate research that introduced them to varied views of safety. Nonetheless, we believe both lab courses make safety learning more consistent by leveling their knowledge of safety, its importance, and its application in the chemical engineering practice.

To further reinforce safety concepts practiced in the laboratories and highlight their importance in the industry practice, we invite one guest lecturer on process safety management. We typically invite alumni from our department to discuss process safety in industry, hazard identification, risk analysis, and risk management. This lecture is also a great chance to strengthen our relationship with industry partners, welcome alumni to visit our department, highlight the important of process safety in industry, and allow for spaces of communication between our students and safety professionals.

The next step in the safety sequence in the course are the one-on-one safety meetings with industry professionals.

Safety Meetings with Industry

As previously discussed, all students registered in the senior year laboratory complete a class project for which they must develop their own safety rules and policies after identifying and defining all potential experimental hazards. As part of this project, and after students have completed all required safety training, teams meet one-on-one with industry professionals to gain new perspectives and deepen their process safety knowledge. We utilize these meetings to increase our safety collaborations and to create additional avenues for process safety discussion and learning. By these meetings we also open new opportunities to reinforce the safety culture in our students: students hear directly from industry practitioners how safety needs to be a priority to every new chemical engineering graduate.

During these meetings, students discuss the typical approach to process safety in the chemical industry and also receive recommendations to improve the safety design of their class projects. The meetings proceed as follows:

1. Students are assigned to an experiment station during the second week of classes. As previously detailed, they prepare a proposal which includes a safety section.

2. We receive a list of volunteers from our industry partner. These are the professionals that will participate in the safety discussions with our students.

3. Student teams are paired with one industry professional based on their area of expertise. We share their contact information and request students to start communication with them by sharing a copy of their proposed project and their proposed safety approach.

4. The team safety officer contacts the industry professional and suggests times to meet to discuss project safety in more detail. Students are required to prepare an agenda for the meeting, this agenda helps us ensure students make good use of the meeting time. All files and communications are shared with the teaching assistant working with each team.

5. Students meet industry professionals, teaching assistants are also in attendance to ensure meeting quality and help with any communication issues. Meetings usually last 1 to 2 hours. During this time, teams discuss laboratory safety, process safety, and safety career paths for chemical engineering graduates.

6. After the meetings are completed, students modify their project safety approach based on recommendations received and they prepare a safety summary.

The teaching assistants play a key safety role: they help students implement safety recommendations and guide students as they complete their experimental work. They also participate in the scheduling of the safety meetings and facilitate the creation of a meeting agenda to optimize the use of their time.

After meetings are completed, teams work on the experimental section of their class projects over a four-week period. Teams complete their experiments following their own experimental and safety procedures, and also include safety recommendations received during the safety meetings.

The class project concludes in a poster session for which teams also prepare a summary of their approach to safety. In this safety report, students define safety aspects required to scale up their experiments as well as considerations related to the implementation of their project in an industrial setting. Students submit a summary of the meetings detailing elements of safety they were able to improve as a consequence of the meeting with industry professionals.

By the end of the semester, students create a safety report that summarizes safety in the laboratory. This final safety report includes 3 main sections:

1. Laboratory safety: The final laboratory safety section includes the safety section from the project proposal and any improvements and updates made as a result of the meetings. Student’s detail and explain the reasons behind any changes made to this section. In addition, they describe their strategy to minimize/mitigate risks associated with their identified main experimental safety concern.

2. Process safety: This section includes a description of the safety aspects to consider when scaling up a process to industrial size, safety aspects relevant to the creation of new process, and safety aspects that would be required to scale up their experimental project in particular. Teams are encouraged to discuss these questions with their assigned safety professional and list their recommendations in the final submission.

3. Safety meeting summary: this is a short summary of the safety experience during the semester. Teams detail how they accomplished all their safety objectives during the industry meetings, explaining how they discussed and examined all necessary laboratory and process safety aspects. They also summarize their main findings form the industry meetings (i.e., what did you learn? How did the meeting help you perception and understanding of safety?) and provide recommendations to improve the meetings in

future semesters. We share some of these summaries with our industry partners to promote continuous improvement.

The final aspect of the practice of safety in the laboratories is the labeling and disposing of chemical waste generated by student teams while working on projects. Teams are required to label all their chemical waste and dispose appropriately in consultation with the teaching team. After labeling, students work with each TA to submit a disposal request to EHS and they must also reserve a time to clear their work area and ensure all chemical waste was properly disposed.

Project-Based Learning Integration.

In the foregoing, we have described the safety experience implemented in our laboratory courses. All safety elements in the courses intend to prepare students for the practice of safety in their post-graduation careers. To further promote the development of safety skills, we utilized a PjBL approach. To incorporate PjBL in safety in the courses, we centered on the six key features of the PjBL framework [12], [13], [20]:

1. **Including a driving question:** this is accomplished by the individual project preproposal and the team proposal. Both proposals must integrate safety to demonstrate feasibility of the proposed project. Students must identify and analyze safety considerations as they refine their research questions. In addition, they need to identify and create strategies to mitigate one main safety concern associated with their experiments.

2. **Focusing on learning goals:** The safety learning goals are delimited by each project proposal and further expanded in the safety assignment. Student teams implicitly implement safety as they determine whether their project can be safely completed in the laboratory. Moreover, the safety report assignment guides students on the safety aspects to consider in their projects.

3. **Engaging students in scientific practices:** Students create their own experimental procedures, safety rules, and policies. They engage in scientific safety practices by incorporating these procedures experimentally. Furthermore, the safety meetings with industry help our students improve their safety procedures and understand the importance of safety while working in consultation with an industry practitioner.

4. **Centering in collaboration:** All project work is completed in student teams and their safety efforts are led by the team safety officer. They also collaborate with the TAs and industry professionals as they improve their safety laboratory practices.

5. **Using technology tools to support learning:** students are completely free to design their experiments and determine the type of measurements, data to gather, and software packages necessary for data recording and analysis. This also requires them to design their experiments to be safe. For example, students working on CO_2 adsorption must examine the system and decide if they need to use a vacuum line, an external CO_2 analyzer, or piping rated for their experimental pressures to ensure their experimental work area is safe at all times.

6. **Allowing the creation of tangible products and artifacts:** The project culminates in a poster session for which teams also prepare a summary of their approach to safety. This safety summary detailing their learning and their safety procedures in the laboratory is the final safety product developed from the courses. Students also reflect on the strategies their pursued to mitigate/minimize risks. Additionally, as required by the PjBL framework, knowledge is created by students through their safety section and experimental safety strategy. This knowledge is expanded as they analyze and discuss the main safety requirements in the scale up of their project to industrial size.

RESULTS AND DISCUSSION

To validate our results and to continuously improve the safety experience, we conducted a survey to collect feedback from students in the Senior Laboratory during one academic year (i.e., two semesters). We collected data from senior students that have participated in both laboratory courses. The end goal of our survey was to understand whether our safety approach enhances the undergraduate safety culture by improving the awareness and appreciation of safety in our students. We were also interested in understanding whether we were being effective at integrating practical safety elements to our laboratories, and if the overall student perception of safety as a priority to the chemical engineering profession was cemented by the courses.

An end-of-semester survey was administered in Qualtrics during the last day of classes (i.e., the day of the final poster session). The survey contained four Likert-scale questions. All survey data was collected electronically. The use of survey data was approved by the Institutional Review Board at the University. Participation in the survey was voluntary.

Likert-scale questions surveyed students on their overall perception of safety in the courses using a 5-point scale as follows: “1=Strongly Disagree,” “2=Somewhat Disagree,” “3=Neither Agree nor Disagree,” “4=Somewhat Agree,” and “5=Strongly Agree.” We explored 4 main areas through these questions:

- Q1 – Perceived increase in safety knowledge after participating in the courses.
- Q2 – Increased awareness and appreciation of safety after completing the courses.
- Q3 – Interest and engagement in the one-on-one meetings with industry professionals.
- Q4 – Understanding of safety as a priority to the chemical engineering practice.

A total of 125 students participated in the survey: 71 in Spring 2023 (79%, 90 students registered) and 54 in Fall 2023 (100%, 54 students registered). No other identifying characteristics were recorded; the goal of the survey was to understand the overall perception of learning of all students rather than that of a particular group of students. To further simplify data visualization, we grouped answers to these questions in three categories:

1. Positive perception if students strongly agree (5) or somewhat agree (4)
2. Neutral perception if students neither agree nor disagree (3)
3. Negative perception if students somewhat disagree (2) or strongly disagree (1)

Figure 1 summarizes the survey results.

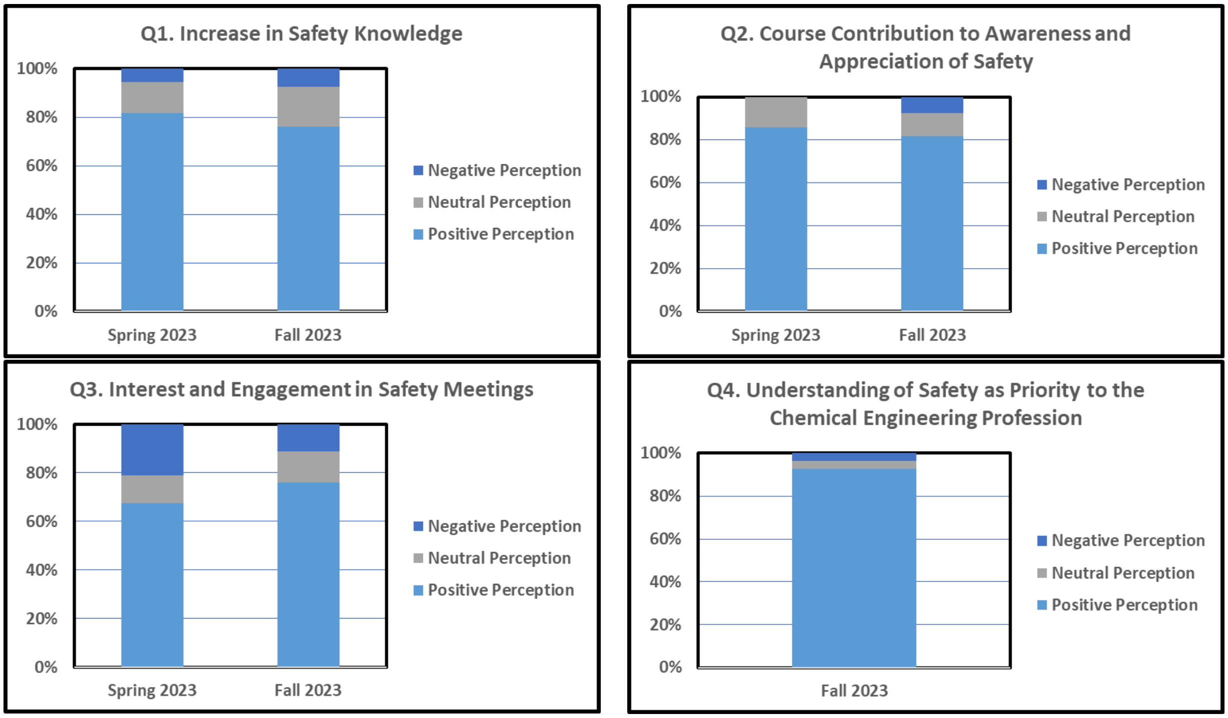

Figure 1. *Safety Survey results during Spring 2023 and Fall 2023.*

As depicted in Figure 1, students had an overall positive perception of the laboratory safety experience and its benefits to their learning. Our results indicates that most students perceive the courses as contributing positively to their safety knowledge (>75%). While we cannot claim this is directly related to the practice of safety in the labs (i.e., they could be learning more about the theory of safety), the data show that students understand the safety elements of the courses as beneficial to the development of their safety expertise. In addition, more than 80% of students considered the courses to contribute to their awareness and appreciation of safety. We hypothesize this is due to all the practical safety elements in the courses: the creation of a proposal with a safety focus, the freedom to experiment and propose their own safety approach, and the discussions with industry that showcase the importance of safety in the practice of chemical engineering.

Figure 1 also indicates a majority of students perceived the meetings with industry as engaging and interesting (>67%), reinforcing our view that these meetings and discussions are beneficial to increase awareness of safety aspects beyond course work. Lastly, almost all students registered in the course in Spring 2023 (93%) considered that the understanding and practice of safety must be a priority to the chemical engineering profession. We believe all the opportunities to practice and discuss safety throughout the program contribute to cementing this view of safety as a priority in the practice of our profession (note: we were not able to records data for this last question in Spring 2023 due to a problem with data collection in Qualtrics). All survey results suggest that the courses effectively contribute to create a safety culture in our students that will help their transition to the workforce.

In future semesters, we will collect additional student feedback through open-ended survey questions to further improve the practical safety training experience. Moreover, we plan to work with our industry partner to implement a class project focused on process safety. This potential project will target students interested in a safety career to make sure they practice safety and learn about its applications in more depth.

CONCLUSION

We have updated and enhance safety learning in our undergraduate laboratory courses by creating a safety sequence, integrating project-based learning, and revamping our industry collaborations. By this improved sequence, we have pursued the gradual development of a safety culture in our students. Our main focus has been on prioritizing safety and introducing our students more effectively to the practice of laboratory and process safety. To accomplish our objectives, we have utilized external safety training, practical laboratory elements, PjBL tools, team discussions, and industry collaborations. Our survey results confirm that the courses increase safety awareness and effectively contribute to an improved safety culture in our students. We believe this enhanced safety awareness will help our students in their transition to the workforce. In addition, this improved perception of safety facilitates the formation of engineering leaders that understand the importance of safety to the chemical engineering profession.

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