2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering
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ASEE
Paper ID #38527

# Open-Ended Experiential Learning Opportunities in the Chemical Engineering Unit Operations Laboratory: A Qualitative Research Study

**Dr. Erick S. Vasquez, University of Dayton**

Erick S. Vasquez is an Associate Professor in the Department of Chemical and Materials Engineering at the University of Dayton. He received his B.Eng. in Chemical Engineering at UCA in El Salvador. He obtained his M.S. from Clemson University and his Ph.D. from Mississippi State University, both in Chemical Engineering. His laboratory research involves nanotechnology in chemical and biological processes. His educational research interests are community-based learning, open-ended laboratory experiments, teamwork, collaborative and active learning, and Transport Phenomena computational modeling.

**Kelly Bohrer, University of Dayton**

Kelly Bohrer is the Executive Director of the ETHOS Center, a community engagement center connecting students, faculty, and staff with NGOâ€™s around the world for technical projects as part of immersions, teaching, and scholarly activity. She also is th

**Dr. Matthew Dewitt, University of Dayton**

Matthew DeWitt is a Distinguished Research Engineer at the University of Dayton Research Institute. He received his B.S. in chemical engineering from The Ohio State University and his Ph.D. in chemical engineering from Northwestern University. His resea

**Soubantika Palchoudhury**

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## Abstract

Over the past few years, senior-level chemical engineering students in the Unit Operations laboratory at the University of Dayton have obtained unique experiences performing open-ended experiments emphasizing experiential learning theory (ELT) aspects. During the last six weeks of the semester, students conduct a final project where they define an objective and propose a methodology for a more advanced study than required in the earlier portion of the course. The authors (instructors of the course) provide (1) ideas for experimental topics of interest which are applicable to chemical engineering students, 2) focused research opportunities with faculty members or local entrepreneurs and businesses, and 3) community-based learning experiences with the ETHOS center at the University of Dayton. Once the instructor approves a student-centered experiential learning project, the students define the specific objectives, perform experiments or simulations, and summarize the analysis and findings in a final technical report or memorandum. After submitting the final report, students also provide a written reflection of their work and learning experience.

In the most recent academic semester, various open-ended topics were made available to the students, including coffee-processing-related unit operations, environmentally sustainable biodigesters, and kombucha fermentation. This paper highlights open-ended experiential learning final project opportunities (n = 6) in the Chemical Engineering Unit Operations laboratory, provided to 16 teams of 3 - 4 students per team (n = 53). We discuss the instructors' observations and perspectives and a summary of students' written reflections. The authors performed qualitative assessments using coding and thematic analysis on the students' team-written reflections. Four central student themes emerged: cognitive, affective, relational, and pedagogical. The authors also summarize their findings and provide perspectives for open-ended, experiential learning opportunities in Chemical Engineering laboratory-based courses. Overall, the qualitative analysis indicated the teams enjoyed the opportunity to select an open-ended project and the independence, autonomy, and control over the experiment stage. These results confirmed the student-centered approach in experiential learning projects for the Chemical Engineering Unit Operations laboratory previously attained in other STEM-related courses

**Keywords:** Unit Operations Laboratory, Experiential Learning, hands-on experiments, open-ended laboratory experiences, Qualitative Analysis.

## 1. Introduction

The Unit Operations Laboratory is a unique and abiding hands-on experience for chemical engineering undergraduate students (ChE). Students implement the knowledge gained in multiple undergraduate courses into studies utilizing a range of unit operations equipment available in the laboratory. This laboratory course is typically the first time many chemical engineering students have the opportunity to work with pilot-scale equipment, facilitating a unique laboratory practice and experiential learning experience during their undergraduate career [1]. Additional professional skills are developed by students working in the laboratory, including teamwork, experimental designs, technical written and oral communication, and critical thinking [2]–[4]. The combination of practical and professional skills within the Unit Operations laboratory could successfully allow students to complete experiential learning within their undergraduate curriculum.

Open-ended laboratory experiments help students to engage, learn, and explore different topics from a hands-on experience perspective [5]. Although there are countless solutions to problems in industrial applications, open-ended assignments in the classroom or the laboratory are often challenging to implement as there is no unique solution or approach to solution. Instructor challenges include defining reasonable expectations to be achieved, an appropriate grading methodology and sufficient time allocation for interacting and mentoring students. Despite these challenges, a few studies have emphasized the need to implement these types of problems in the classroom [6], [7] or in the laboratory [8]. Engineers are known to be problem solvers and create solutions; hence, integrating open-ended problems or learning by doing could lead to authentic experiential learning activities in forming engineers [9].

According to Kolb's experiential learning theory, constructive learning occurs during four phases: abstract conceptualization, active experimentation, concrete experience, and reflective observation [10]. In this iterative cycle, students have autonomy in learning and must constantly reflect on achieving desired outcomes. For example, a 10-year study showed that applying Kolb's learning cycle has led to deep learning and longer concept retention [11]. Previous studies in the Chemical Engineering Unit Operations Laboratory demonstrated that incorporating project-based laboratory aspects with experiential learning leads to deep learning and effective instruction [5], [12], [13]. The entrepreneurially minded learning (EML) framework based on the 3 Cs of curiosity, connection, and creating value also support student-centered learning experiences, as demonstrated in the classroom and the laboratory [14], [15].

In this study, we aim to qualitatively assess the implementation of open-ended final projects in the Chemical Engineering Unit Operations Laboratory with experiential learning components. This remaining sections of this paper include:

2. Experiential Learning in the Unit Operations Laboratory: Open-Ended Final Projects Overview
3. Results and Discussion: Instructors' Observations Regarding the Feasibility of Experiential Learning Final Project Assignments
4. Qualitative Analysis, Methods, and Theme Coding of Student Analyses Obtained from Written Reflections Provided by Each Team
5. Conclusions and Recommendations

## 2. Experiential Learning in the Unit Operations Laboratory: Open-Ended Final Projects Overview

The primary goal in the final six weeks of the course is to require and encourage the students to pursue an final project experiment where they define an objective and propose a methodology for a more advanced study compared to the traditional laboratory experiments (A description of the Unit Operations Laboratory instruction can be found in **Appendix A**). For the final project, the students have the freedom to either utilize existing apparatus in the laboratory, or to propose (and possibly fabricate) a novel test for investigation. To assist in this effort, the instructors of the course provide ideas for (1) "conventional" experimental topics of interest which are applicable to chemical engineering students, 2) focused research opportunities with faculty members or local entrepreneurs and businesses, and 3) community-based learning with the ETHOS center at the University of Dayton. The ETHOS center provides engineering students with international and domestic immersion opportunities during academic breaks, where they apply engineering knowledge and concepts in different environments. The "conventional" topics typically utilize existing experimental apparatus with an expanded focus of study and technical depth compared to expectations during the first half of the semester. The focused research opportunities and community based learning opportunities typically have a well-defined objective with expected deliverables, but are open-ended with respect to experimental design, test and evaluation.

ChE students have the opportunity to discuss the potential topics of interest with both the instructors and teammates to assist with identifying the appropriate selection for their project. Each team proposes the topic and primary objectives to the instructor for discussion and feedback. Once the instructor approves a student-driven project, students proceed to accomplish the defined objectives by performing experiments or simulations, and summarizing the analysis and findings in a final technical report or memorandum. With respect to the focused research and community-based learning opportunities, several potential topics were discussed during the Fall 2022 academic semester; these topics were selected as there were existing faculty and industrial partners readily available with interest to participate. Students were asked to rank their top three project choices. Once all the teams in all the selections made their selections, the instructors met and assigned the final projects based on the suggested rankings. The instructors targeted different experiments for each team in each laboratory section to avoid repetitive final presentations. A brief description of the open-ended, experiential learning opportunities pursued in the Fall 2022 semester are described in the following sections.

### *2.1 Biodigesters*

The Hanley Sustainability Institute and Food Services Office at the University of Dayton have active efforts for reducing on-campus food and dining-related (e.g., paper, cardboard, etc…) wastes. The primary method currently used for reclamation is via composting. The potential exists for both enhancing the efficiency of the reclamation process and generating high-value products (most notably methane) by using biodigestion. The primary requirement of this project was to utilize waste obtained directly from the Food Services Office while employing simple designs for the biodigester system. A simple biodigester design utilizing readily available and inexpensive materials was proposed by the laboratory manager with input from the student teams. All teams used separate biodigesters with identical design; due to the length of time required for the anaerobic fermentation process to proceed, each team selected a specific variable for study with a common control biodigester. The teams worked with the instructors and lab manager to define variables of interest which could be investigated within the limited time available. These included the type of inoculant (**Figure 1**), ratio of inoculant to organic waste, passive versus active mixing within the biodigester, and the initial liquid pH within the biodigester. The primary metric of performance was the formation rate and composition of the generated gaseous product. The teams attempted to compare the experimental results to those predicted using appropriate models.

**Figure 1.** A ChE student adding inoculant obtained from a local water treatment plant to be blended with organic residues prior to sealing the biodigesters  [Photo provided by a student].

### *2.2 Nanofertilizers*

A unique nanofertilizer formulation was provided with the intent to introduce students to the food and agri-technology industrial sectors. The nanofertilizers were developed in-house by Dr. Palchoudhury at the University of Dayton with a provisional patent recently filed. The students investigated the effect of the new nanofertilizers on the germination rate, growth rate, and chlorophyll content of various crops, including corn, broccoli microgreens, broccoli, and lettuce, under different soil conditions (**Figure 2**). Multiple experimental variables were available to students, including the amount and type of nanofertilizer used, watering frequency, and sampling time. Overall, students were introduced to proper design of experiments, utilization of control experiments (i.e., no nanofertilizer), and non-traditional unit operations instrumentation techniques. The latter included Fourier transform infrared spectroscopy (FT-IR), Dynamic Light Scattering (DLS), and a chlorophyll meter. A representative result is that the students determined that the nanofertilizer-treated sample sets' growth rate were higher than the control for the 14-day span during which the measurements were recorded.

**Figure 2.** A ChE student adds nanofertilizers to corn seeds to determine their effects on the corn plant growth rate [Photo provided by a student].

*2.3 Fermentation: Kombucha, Beer, or Wine*

Projects utilizing fermentation allow the investigation of many potential variables on the kinetic rate and extent of alcohol formation and provide the opportunity for an open-ended experimental study. In addition, there are many developed models in the literature for comparison, where the corresponding parameters can be determined via regression with the experimental data. This allows a more rigorous kinetic analysis of the data to be performed. Moderate volumes for each fermentation experiment (~ 1 gallon) are feasible, which provides flexibility for time-dependent sampling and analysis. The teams can utilize different analytical techniques for quantitation of relevant parameters (e.g., specific gravity, alcohol concentration, cell count, handheld density meter, wireless airlock hydrometer systems). Many variables can be readily considered, such as the impact of the type and concentration of the active yeast, source of sugar (e.g., added fruit, types of sugar), and the temperature of the fermentation vessel (by utilizing external water baths).

*2.4. Liquid-Liquid Extraction*

One of the laboratory instructors has developed a mixer-settler liquid-liquid extraction apparatus (**Figure 3**). Over the past two years, students have been challenged to design an experiment to extract ethanol from water using a non-toxic, organic solvent. Selection of the proper solvent for the raffinate phase has been a major challenge. During the Fall 2022 semester, students were allowed to change the three solvents; a team decided to study the extraction of caffeine from water using limonene. Small scale experiments were performed in 20 mL scintillation vials prior to performing the continuous process in the mixer-settler apparatus (Figure 3, inset). Several parameters could be manipulated during the extraction process, including solvent ratios (water to limonene), caffeine concentration, mixing speed, and pumping speeds. Additionally, students learned to perform UV-Visible spectroscopy measurements to analyze concentration changes during and after the extraction/settling process.

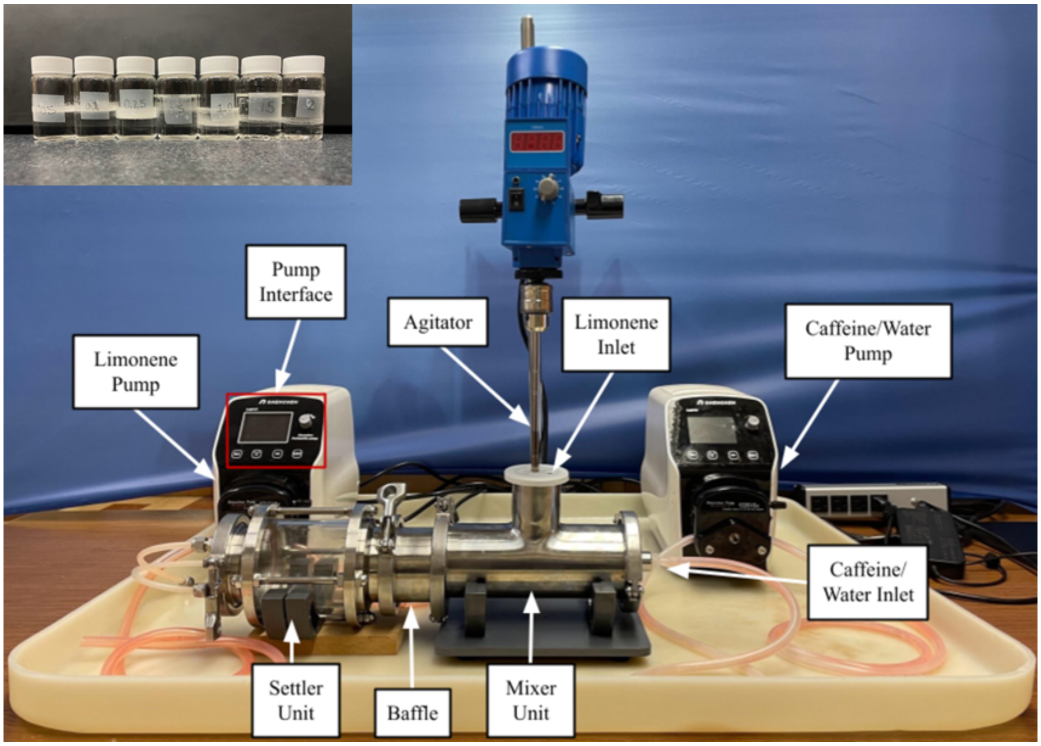


**Figure 3**. Experimental setup used for the extraction of caffeine from water using limonene [Inset shows small lab scale experiments performed to determine proper solvent ratios; Photos provided by the students].

### *2.5 Roasting of Coffee Beans*

The roasting of coffee beans is of high commercial interest (> $100 billion annual revenue), and can be conducted at various scales, including large volume production for general consumer sales and smaller-scale (e.g., niche) applications for specialty types and flavors of coffee. The drying process involves various transport phenomena (e.g., heat and mass), with several potential variables of study (e.g., drying temperature, time, active air mixing). Through visual inspection, the degree of roasting can also be determined (**Figure 4**). The instructors identified a local small business which performed in-house drying and roasting utilizing a pilot-scale (~ 10 lb maximum load) heated rotating drum assembly. The local business was primarily interested in recommendations on potential improvements to the drying process and methodology for enhanced product quality and yields. The teams met with the owner of the business to obtain background on the existing process in use and desired outcomes. Using the same type of drum roasting assembly as the local business, but at a laboratory scale, the teams identified the pertinent variables of interest needed for quantitative analysis of the data obtained, and performed further analysis via development and/or comparison to transport theory and correlations. Additional engagement with a UD Chemical Engineering alumni working in the coffee industry was also possible through a virtual meeting, where several industrial coffee-processing processes were explained. The instructors believed these were important factors to ensure a sufficient level of technical depth to the study. This project allowed the teams to discuss the primary findings and conclusions directly with the business, providing a direct link to an actual near-term application of the findings of the study. A different local company also supplied green coffee beans to the students in the laboratory.

**Figure 4**. Color comparison of coffee beans roasted at the same temperature (~ 460 F) at different times. A dark roast was obtained after 14 minutes of roasting in the rotating drum [photo provided by students].

*2.6 Industry Clients*

Students also had the opportunity to collaborate with an industry partner in a project related to a drying process. The main task consisted in developing a new unit operation experiment capable of determining drying rates of four unspecified samples. Students and instructors working in this project signed a non-disclosure agreement (NDA), which added an extra layer of complexity when working in experiential learning projects with external stakeholders. It is important to note, however, that weekly virtual meetings, constant communication via e-mail, and a face-to-face meeting with practicing engineers occurred during this experiential learning project. This unique opportunity also opened a window of collaboration with industrial partners, in particular for students who did not have prior co-op experiences in the past.

## 3. Results and Discussion: Instructors' Observations Regarding the Feasibility of Experiential Learning Final Project Assignments

The various projects selected for detailed study during the Fall 2022 semester encompassed a wide-range of technical areas with varying maturity levels. This provided many opportunities to define and pursue creative and novel technical objectives with the opportunity to interact with external collaborators. This allowed a wider range of potential topics to be considered than if only existing laboratory resources and unit operations were utilized. However, this approach required the students to be proactive and specifically put forth time and effort early in the process due to the limited available time and the non-structured teaching process. Despite the broad range of technical areas and focus of study, the instructors noted specific observations which were related to thematic aspects of the projects. Some common themes and the corresponding observations made by the teaching instructors are discussed below.

### *3.1 Projects with Well-Defined Experimental Systems and Operating Parameters*

Projects which utilized well-defined (or existing) experimental systems or had established protocols and methodologies facilitated a larger number of trials with larger data sets. These included the projects related to evaluation of Nanofertilizers and Roasting of Coffee Beans. Student groups working with these types of projects could rapidly identify technical objectives and begin experimentation during the first week. This increased the total available amount of experimental time allowing for a wider range of experimental variables and parameter space to be considered in the study. The teams also had more time to reflect and identify appropriate models/correlation for comparison to the experimental results. However, when utilizing existing apparatus, there was difficulty identifying potential modifications to the hardware or adapting the testing methodology for enhanced data acquisition. This typically was necessary to provide additional or required data for comparison to theory and models/correlations. An example was the need for quantitative measurement of the time-dependent temperature of the coffee beans to model the corresponding drying and roasting processes; the drum assembly had a single centerbody temperature measurement location. Some teams struggled with determining an appropriate method to obtain statistically relevant data (e.g., use of IR temperature sensor to directly measure surface temperature of beans). The use of pre-existing apparatus and testing methodologies was also observed to reduce the creativity in experimental design, with less interactions with students or instructors from other sections. Communication and interactions with the internal stakeholder (i.e., the faculty instructor) interested in Nanofertilizers occurred periodically through weekly in-person meetings; however, the interactions with the external stakeholder supporting the coffee roasting experiment were limited. Some of the students showed frustration with the lack of direct guidance or support from the external partner, as some were interested in learning more about the entrepreneurial process in coffee roasting.

### *3.2 Projects with Open-Ended Experimental Design with Less-Defined Applications*

Projects that were more open-ended and exploratory in nature provided the students with the opportunity to be creative in defining the experimental objectives and approach. The teams had more freedom to develop and propose novel objectives while considering a wide range of parameter space. This facilitated increased interactions with students from other sections, instructors and the internal/external stakeholders. There was increased motivation to create value (e.g., a working experimental capability for the liquid-liquid extraction system) while providing further opportunities for future students, faculty or external clients. Despite these many favorable factors, the nature of these types of studies presented challenges for the teams. Initiation of the experimental design and testing was slower, which reduced the total time available for testing and the corresponding amount of data that could be collected. In addition, delays in obtaining necessary supplies and hardware required for testing occurred for teams which did not begin the process prior to completion of the first half of the laboratory course. Teams which were not proactive with defining the technical objectives and experimental design at the onset of the projects significantly reduced the amount of quantitative data that could be obtained. A further manifestation of this issue was an increased level of stress for the teams to obtain (any) quantitative measurements or appropriate comparison to theory/models which could be incorporated into the final project report (which comprised 20% of the team grade). The instructors also noted that these teams expected a higher level of direct guidance and assistance from the instructors and laboratory manager, which adversely impacted their ability to proactively identify actionable tasks with viable outcomes.

### *3.3 Projects which Required Additional Research and Preparation*

Projects with technical areas of focus which were more “specialized” (e.g., not covered in detail in the core Chemical Engineering Curriculum) provided additional experiential learning opportunities. The students could review literature and seek out subject matter experts (typically faculty members at the university) to obtain improved understanding in the technical area. They had the opportunity to utilize experimental and analytical techniques that were not typically incorporated into the curriculum. However, insufficient effort and understanding of the pertinent processes and theory, as well as other courses’ demands, adversely impacted the quality of the experimental approach and resulted in inefficient use of experimentation time. An example of this situation occurred with the biodigester projects, where an insufficient understanding of the anaerobic digestion process and necessary operating conditions resulted in negligible product gas yields for 2-3 weeks. This presented a difficult situation for the instructors, as they had to decide whether to intervene in the process, or allow the teams to learn via trial and error. An additional challenge observed was that some teams had difficulty defining a leader and proper workload distribution due to the lack of research-oriented experience.

### *3.4 Projects with External Collaborators or Faculty Interactions*

The teams which performed projects with the external collaborators and research faculty benefitted from having a direct application to help define the technical objective and variables of interest. Depending on the overall scope of interest, the teams could consider either basic or applied aspects for study, and the direct collaborations facilitated the ability to obtain relevant background and guidance on the technical subject material. However, the defined application did constrain the allowable experimental approach and methodology due to the specific needs of the collaborator (e.g., the industry-sponsored project). The instructors also had to consider the collaborators' needs, in addition to the desired academic objectives to be achieved in the laboratory course. A balance between technical and educational deliverables was explained to all the parties involved, which helped the experiential learning process and is suggested for future collaborative efforts in the laboratory.

## 4. Students Reflections and Assessment of Experiential Learning Project Opportunities

### *4.1 Deliverable*

A reflection document (1 - 2 pages) was requested from each team (n = 16) participating in the Unit Operations Laboratory during the Fall 2022 semester. We attempted to obtain objective, honest feedback from the students, and a separate assignment from the technical report and presentation was assigned. The assignment instruction was an open-ended single prompt, specifically related to the final open-ended assignment involving the unique experiential learning component as follows:

> *"Please submit a 1 - 2 page reflection about your experience in the final project. We want to take your feedback to improve and learn for future Unit Ops years. Please include all positive and negative experiences as well as suggestions for us, the instructors. "*

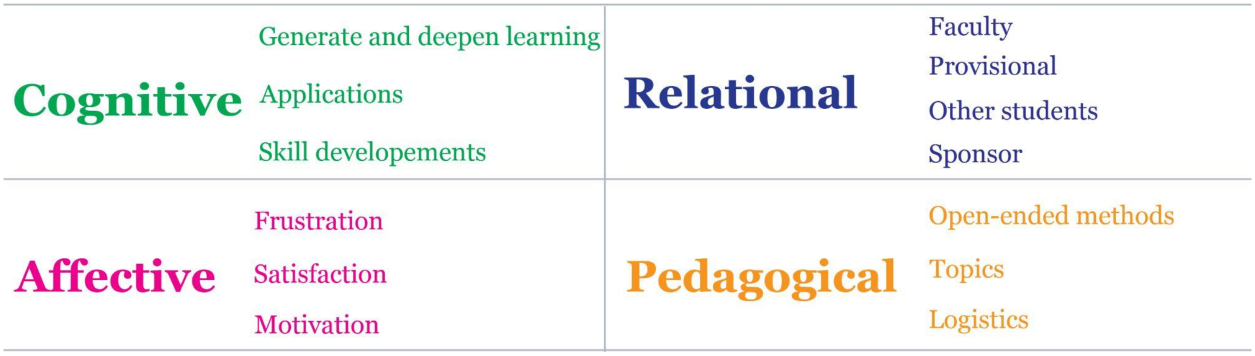
The instructors only reviewed student reflections once the final course grades were submitted, and these documents were solely used for this study.

### *4.2 Methods of Analysis*

For qualitative thematic analysis of the student reflections, a member of the research team who does not teach the laboratory and was not informed about the prompt for the reflection papers used an iterative and inductive approach to build a code book. To begin, each reflection paper was read for familiarization with data, and an initial set of codes was generated using in-vivo and descriptive coding methods. From this initial set, a coding book was built using a mixed hierarchical/flat coding frame (e.g., all codes are listed separately and each are split into negative and positive groups), and this framework was used to code all reflection papers. Codes were categorized and thematic analysis performed to develop descriptive themes, which were then grouped into dimensions (*cognitive, affective, relational, and pedagogical*). The frequency of each code was recorded.

### *4.3 Students Reflections: Coding Results and Discussion*

Four dimensions, with several themes categorized into each dimension, emerged from the qualitative thematic analysis: *cognitive, affective, relational, and pedagogical* (**Figure 5**). Additionally, students were encouraged to provide suggestions/recommendations for future implementations. This part of the reflection papers was analyzed using a descriptive content analysis to identify recommendations and summarize the most and least frequent recommendations.



| | | | |
|---|---|---|---|
| **Cognitive** | Generate and deepen learning<br>Applications<br>Skill developements | **Relational** | Faculty<br>Provisional<br>Other students<br>Sponsor |
| **Affective** | Frustration<br>Satisfaction<br>Motivation | **Pedagogical** | Open-ended methods<br>Topics<br>Logistics |

**Figure 5.** Thematic analysis results obtained from team written reflections describing experiential learning experiences in the Chemical Engineering Unit Operations Laboratory

Different codes were obtained for each theme and were recognized within the four dimensions: *cognitive, affective, relational, and pedagogical*. The complete coding analysis is shown in **Figure 6**. The number of positive (+ n) or negative (-- n) frequencies identified for each code is also presented. Note that the total frequencies are counted every time these appear in a document, which could lead to more than 16 prompts from the original reflection documents. For example, a few instances concur with instructors' expectations for the Unit Operations laboratory course for the cognitive dimension. Several quotes identified the "utilization of past skills and knowledge" while completing the experiential learning final project.

Several positive and negative differences were identified between the traditional unit operations experiments and the open-ended experiential learning experience. The affective dimension category had only positive reviews. Students were highly "satisfied" with completing the project, which included four codes. For example, "independence, autonomy, and control" was highly positive (n= 23) and supported by several students. Example quotes from surveys are listed below.

> *"It (the project) also allowed us to take matters into our own hands and reach out to various contacts to expedite information. We also really liked how it was an open-ended experiment and that we were able to design an experiment based on what we wanted to test."*

> *"The group very much enjoyed taking charge of the experiment and having creative control."*

> *"I really enjoyed the independence of the course, as it is the first time that I have been allowed to fully design and work on my own experiment."*

> *"One of the most positive parts of this project was the level of independence it entailed. This is an important experience because students will probably need to be able to work on unsupervised projects in future industries."*

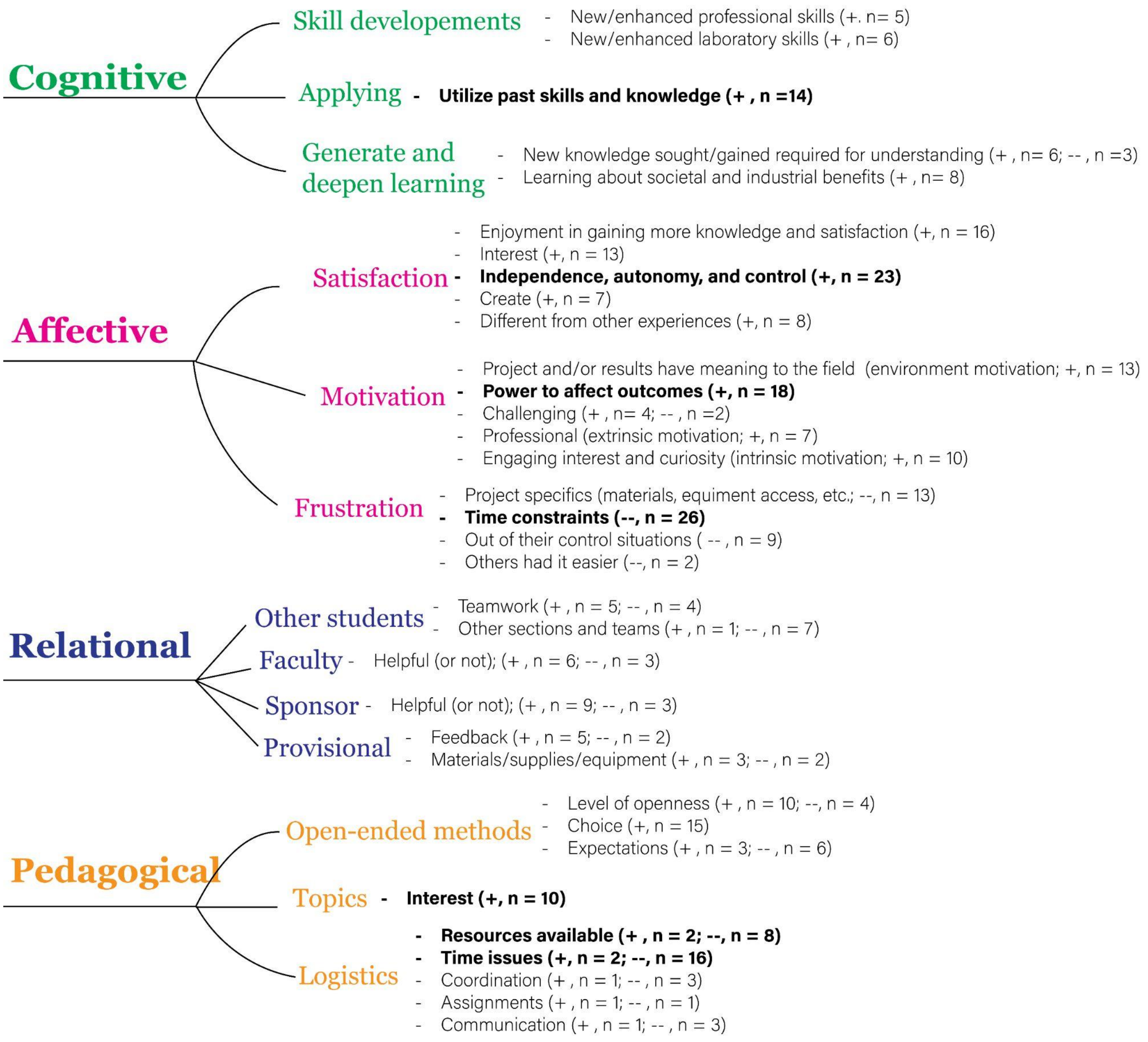


**Figure 6.** Dimensions, themes and codes identified from student surveys during the experiential learning, final project stage in the Chemical Engineering Unit Operations laboratory. [+ signs indicate positive frequencies while **--** signs indicate negative frequencies; frequencies were also counted for instances appearing more than once in each reflection document]

The power/control to affect outcomes was identified as a motivational aspect within the affective dimension. Similarly, interest in the research (experimental) topic and the ability to choose a project led to enhancement in the pedagogical dimension. A few quotes supporting these findings are listed below.

Motivational:

> *"It was incredibly fulfilling to have a project at the end that was done almost completely on our own."*

> *“Having this flexibility in designing our own experiment allowed us to truly be curious and determine things we wanted to know.”*

> *“When my experiment succeeded, it was due to my hard work.”*

Choice:

> *“I enjoyed that we got to pick out final projects out of multiple that all varied in type.”*

> *“Personally, we believe having multiple project options that differ from the typical Unit Operations Lab curriculum is very influential on the student's ability and willingness to learn.”*

> *"To begin, the best part about this lab was the ability to work on your own experiments and to be given an apparatus to work with and find a way to use your own knowledge and research to test your hypothesis.”*

Some of the most negative findings were observed in time constraints and equipment access within the frustration theme for the *affective* dimension. Although the students had six weeks to complete the final project, thanksgiving break, fall break, and the national AIChE conference led to a reduced number of laboratory sessions. From a logistical perspective in the *pedagogical* dimension, the resources available (e.g., equipment) and time issues were also identified as part of the most negative aspects encountered during these laboratory experiences. A few quotes are also provided:

> *"...the lab providing the physical setup for the biodigesters was very helpful and saved us time while dealing with other obstacles."*

> *"Having a research-style project was rewarding, but it led to a couple of unrealistic expectations relating to how much time we have to gather data."*

> *"Overall the biggest issue was a lack of time. We recommend that more time should be given for the final project to allow time for planning and redirecting the experiment if something doesn't go as planned."*

> *"It was hard to use our time productively when we were waiting on material or devices needed to move forward with our project."*

> *"It also was difficult to gather the last data points while over [Thanksgiving] break and finalize the presentation when we were all off campus."*

> *"Not only was the ordering process rushed and on a strict timeline to ensure experimentation was possible, but there were a lot of things that would have been beneficial if completed/planned before the first section begins their final projects."*

> *" The final project also suffered from a lack of time, as there was so much I wanted to do. Fermentation takes a lot of time and, due to factors outside of anyone's control, we did not have much time to do it."*

A question that drove requesting reflection papers from students was: *Do students enjoy open-ended, experiential learning experiences in the Unit Operations laboratory?*. Not surprisingly, mixed positive and negative results were found. We assigned these coding to the *pedagogical* dimension. Follow-up studies could identify a team's level of performance with the desire to pursue open-ended experiential learning experiments. A few of the quotes from the surveys are listed below.

Positive (+)

> *"I really enjoyed the openness of the project. It allowed us to have to go through the whole scientific process and figure out not only what we wanted to study, but how we were going to carry out the project."*

> *"We liked that this final project was left open-ended. The other experiments that we worked on this year felt more guided and we appreciated this opportunity to make our own objectives and figure out how to analyze our results."*

> *"...I felt that the final experiment with its open-ended nature provided a great learning experience in managing a timeline, material acquisition, working with outside resources, coordinating between multiple teams, and using initiative to accomplish goals."*

Negative (-)

> *"The cons I felt throughout the lab were that we were given very little guidance at times when it would have been helpful."*

> *"Having the experiment objectives be very open ended was both good and bad. ...it also felt like there weren't many parameters to investigate and the ones that applied to our apparatus had very little literature to support us."*

> *"Although having this project be very open ended was very freeing, it resulted in our group meandering too much on otherwise unnecessary data collection before we were able to identify the data we needed to collect to draw useful conclusions from this experiment."*

> *"Although it can be helpful to just be thrown in the deep end for certain skills, for this one specifically, it would have been nice to have been led through some of the basic principles behind creating a methodology or analyzing the statistics of results."*

## 5. Conclusions and Recommendations

The impact and efficacy of implementing open-ended experiential learning final projects in the Chemical Engineering Unit Operations laboratory was assessed via instructors' observations and use of qualitative analysis methodology. For the specific open-ended project topics available, the instructors identified four different experiential learning project scenarios: (1) Well-defined experimental systems and operating parameters, (2) Open-ended experimental design with less-defined applications, (3) Intensive research and preparation requirements, and (4) Reciprocal interaction between students and collaborators or faculty. Each experiential learning scenario resulted in different challenges, significant time commitments, and multiple coordination efforts between student teams in different sections, the laboratory instructors, and external stakeholders..

The basis for the qualitative analysis was made using a 1 - 2 page reflection document requested from each team (n = 16) participating in the Unit Operations Laboratory during the Fall 2022 semester (53 students in total). Each team was requested to describe their experiences (positive or negative) specifically related to the final project assignment involving the unique experiential learning component. An iterative and inductive approach was used to build a code book, where each reflection paper was read for familiarization with data, and an initial set of codes was generated using in-vivo and descriptive coding methods. From this initial set, a coding book was built using a mixed hierarchical/flat coding frame (e.g., all codes are listed separately and each are split into negative and positive groups), and this framework was used to code all reflection papers. Codes were categorized and thematic analysis performed to develop descriptive themes, which were then grouped into four dimensions (*cognitive, affective, relational, and pedagogical*). The positive or negative frequency of each code was recorded.

Overall, the qualitative analysis indicated the teams enjoyed the opportunity to select an open-ended project and the independence, autonomy, and control over the experiment stage. These results confirmed the student-centered approach in experiential learning projects for the Unit Operations laboratory previously attained in other STEM-related courses. Most students also enjoyed the open-ended projects; however, it was evident that providing adequate resources and time to excel at an optimum level is essential for a positive experience. The overall experience for the student will be strongly impacted by the willingness of the students to be proactive and take “ownership” in the learning experience. Defining and limiting the total number of available topics for study with an established subject matter expert (e.g., Instructor, Faculty member, Collaborator) could enhance student commitment, time management and provide better mentoring opportunities for students. The results from this work could help formulate survey questions to assess the effectiveness of implementing open-ended laboratory experiences in other Engineering laboratory courses. A potential option for institutions with larger enrollments would be to offer specific laboratory sections with experiential learning components; additional aspects could be implemented in these sections to improve student preparation with reasonable expectations of required effort.

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## 6. Acknowledgments

The authors acknowledge conversations with Dr. Jeanne A. Holcomb in the Sociology Department at the University of Dayton, who helped with the qualitative and thematic analysis performed on students' written reflections. Mr. Mike Green, the laboratory manager, provided significant laboratory resources and guidance to the students while working on the final projects. The School of Engineering graciously funded the acquisition of raw materials and consumables at the University of Dayton.

## 7. Appendices

### Appendix A: The Unit Operations laboratory at the University of Dayton

We teach the Unit Operations Laboratory during a 16-week fall semester of the ChE senior year. Teams of 3 - 4 students are formed by student selection (most of the time), with a maximum of six or seven teams per section. Depending on the number of students enrolled, three or four sections are available. The students are responsible for performing experiments and troubleshooting chemical processing equipment related to unit operations processes. Over the past few years, and due to small class sizes and equipment availability, the student teams have been able to complete the same sequence of experiments during the semester, as shown in **Table 1**. Completing the same sequence of experiments throughout the semester (Note: not the same equipment), starting with chemical separations (class prerequisite), followed by fluid flow, and heat transfer has led to positive student evaluations and more consistent grading efforts. Because the Fluid Flow and Heat Transfers processes course is taught simultaneously during the semester, students have the opportunity to learn the corresponding theory and associated material either prior to or concurrently while utilizing the knowledge in the laboratory.

**Table 1.** Chemical Engineering Unit Operations Laboratory schedule at the University of Dayton

| **Timeline** | **Experiment** | **Outcome** |
|---|---|---|
| Week 1 | Introduction / Calibration Experiment | 1 -page memorandum |
| Weeks 2 - 3 | Chemical separations or reaction | Report focusing on data collection and analysis |
| Weeks 4 - 5 | Fluid Flow | Full report with introduction, model development, and conclusions |
| Week 6 | Operability Study | 1-page memorandum |
| Week 7 - 8 | Heat transfer experiment | Full report with introduction, model development, and conclusions |
| Week 8 - 14 | Final Project | Complete full report including an abstract and a final presentation |

During the first eight weeks of the laboratory course, the instructors provide the students with the experimental topic and corresponding unit operations. The students perform an equipment calibration experiment, three traditional experiments involving chemical separations (e.g., bubble-cap and packed bed distillation), fluid flow (e.g., pipe flow, two-phase flow), and heat transfer (e.g., varying types of heat exchangers), and an operability study on a pilot-scale unit operation (e.g., filter press, spray dryers). Each traditional experiment and the operability study have a designated team leader who is responsible for assigning roles and providing a brief presentation (5 slides) with the significant results and primary findings of the experimental study. Additional team assignments and deliverables include laboratory reports, technical memorandums, and presentations, as described in our previous publications [3,4,8,15]. This methodology is consistent with conventional laboratory experiences. The students apply academic knowledge obtained in preceding course work to determine and understand how theory and empirical models apply, and sometimes deviate, from the specific application or experimental setups. Hence, the students must identify and specify their objectives and experimental approach using a request to experiment form (**Appendix B**) and define appropriate models and correlations for comparison to the results obtained.

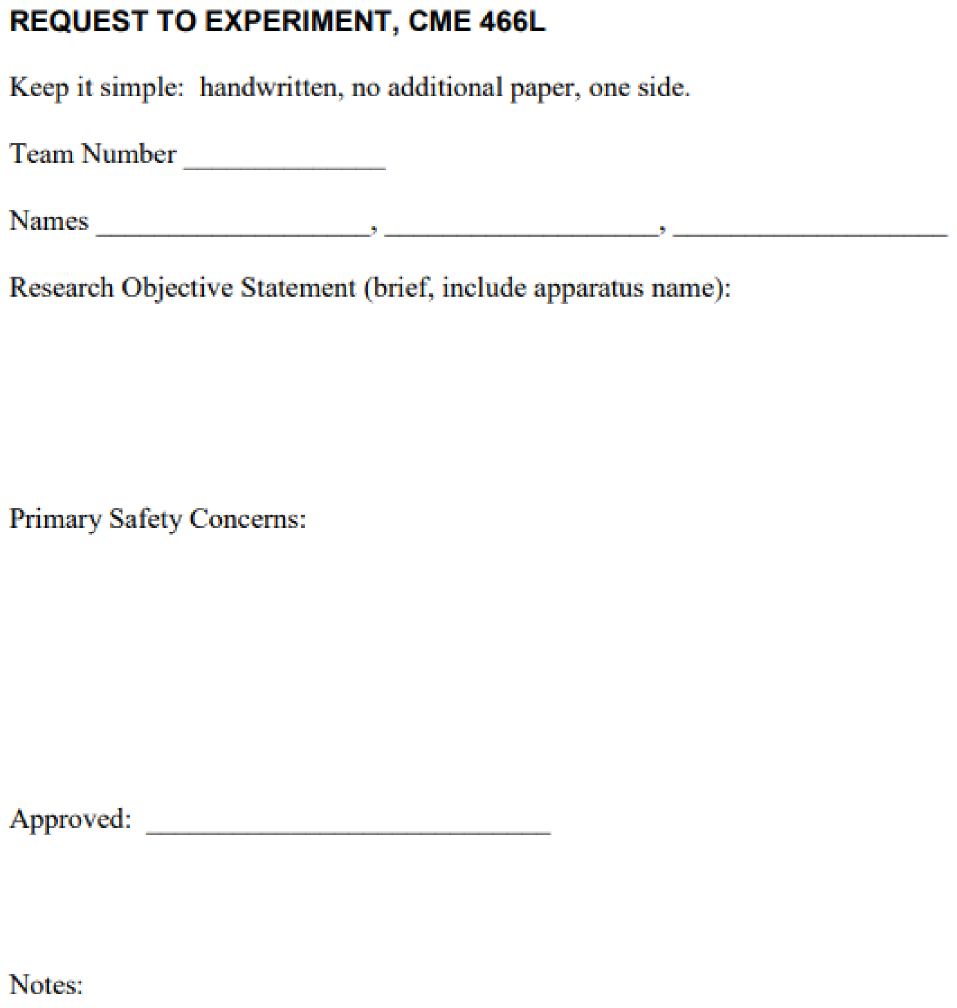
Grades are distributed between individual and team assignment efforts, as shown in **Table 2**. Individual assignments include team lead responsibilities, safety, individual performance, and quizzes, accounting for 25% of the grade. Over the past five years, we have implemented a team lead responsibility where each team member leads an experiment. The individual is responsible for assigning tasks such as data collection and analysis, dividing writing efforts, reviewing and editing the final draft, and briefing the instructor when a report or technical memorandum is submitted. During this meeting, the team leader discusses additional issues (if any) encountered during the semester. Reports and memorandums are a team-based product, and account for a large portion of the grade (75%). We have also implemented team contribution forms (**Appendix C**) to assist students with identifying and addressing team conflicts or low-performer individuals when submitting written assignments.

**Table 2.** Students' individual and team grading contributions for the Unit Operations Laboratory at the University of Dayton

| **Individual Contribution** | |
|---|---|
| Team lead responsibilities/updates | 5 % |
| Final presentation | 5 % |
| Safety performance and quizzes | 5 % |
| Additional quizzes: uncertainty, calibration, data analysis | 5 % |
| Individual performance (Instructor's discretion) | 5 % |
| **Total** | **25 %** |
| **Team Contribution** | |
| Memorandum #1 (Calibration) | 5 % |
| Reports 1 - 3 : Separations, Fluid Flow and Heat Transfer | 45 % |
| Memorandum #2 (Operability) | 5 % |
| Final project report (Experiential Learning) | 20 % |
| **Total** | **75%** |

The final project is performed over a six week period and comprises 20% of the overall course grade. These factors are representative of the importance and expected greater level of effort and detail for the final project. After completing the initial eight weeks, the students have learned to work as a team leader, switch technical roles, and gain different professional and technical skills related to Chemical Engineering Unit Operations Laboratory. Students are usually motivated to obtain good grades and perform well in this final assignment by this point in the semester. Therefore, the instructors have incorporated an open-ended, experiential learning experience for this final project. In the next section, we discuss the different project descriptions available to the students, any stakeholders involved, and the project selection process.

**Appendix B** - Request to Experiment Form.



## REQUEST TO EXPERIMENT, CME 466L

Keep it simple: handwritten, no additional paper, one side.

Team Number _______________

Names ____________________, ____________________, ____________________

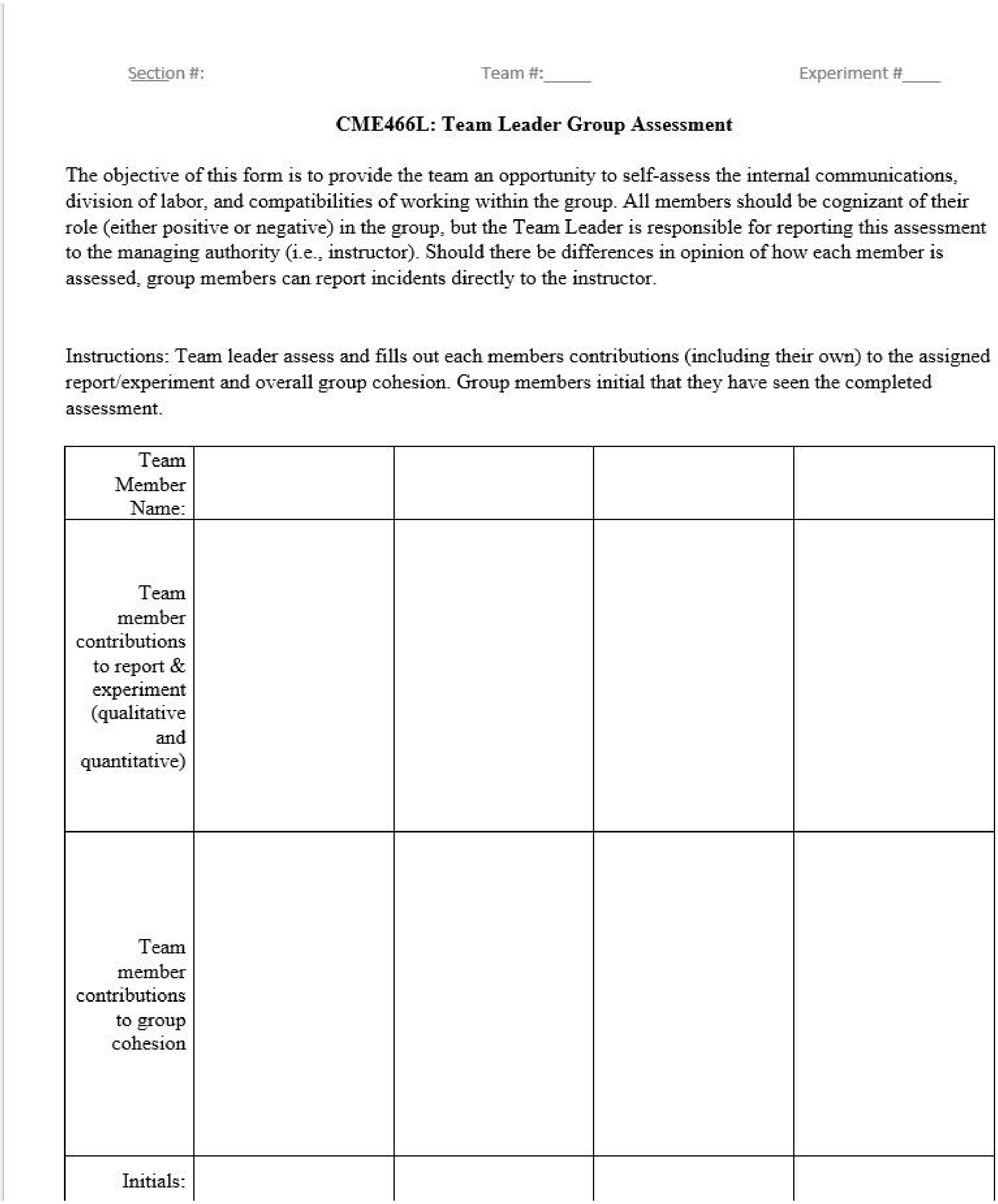
Research Objective Statement (brief, include apparatus name):

Primary Safety Concerns:

Approved: ______________________________

Notes:

**Appendix C** - Team Leader Group Assessment Form



Section #: Team #:_____ Experiment #____

**CME466L: Team Leader Group Assessment**

The objective of this form is to provide the team an opportunity to self-assess the internal communications, division of labor, and compatibilities of working within the group. All members should be cognizant of their role (either positive or negative) in the group, but the Team Leader is responsible for reporting this assessment to the managing authority (i.e., instructor). Should there be differences in opinion of how each member is assessed, group members can report incidents directly to the instructor.

Instructions: Team leader assess and fills out each members contributions (including their own) to the assigned report/experiment and overall group cohesion. Group members initial that they have seen the completed assessment.

| | | | | |
|---|---|---|---|---|
| Team Member Name: | | | | |
| Team member contributions to report & experiment (qualitative and quantitative) | | | | |
| Team member contributions to group cohesion | | | | |
| Initials: | | | | |