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Enhancing Student Engagement and Learning in the Chemical Engineering Laboratory through Contextually Relevant Experiments & Novel Pedagogies

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Daniel Dante Anastasio, Ph.D.

University of Connecticut, 2015

The laboratory course is one of the most critical classes in any engineering program. Engineering by its very nature is a practical discipline, and the laboratory course is usually the first and only class where students are given the opportunity to apply the knowledge they are gaining in lecture courses to real-world equipment. As chemical engineering expands as a field to encompass more elements of bio-engineering, sustainability, and materials science, so too must laboratory curricula update with experiments that present core chemical engineering concepts, such as fluid mechanics, transport phenomena, and reaction engineering, in the context of the broadened discipline. Furthermore, as student demographics begin to change to reflect students having easy access to information and increasingly high expectations for their education, the way the laboratory is taught must also be updated to engage the new generation of students on their own terms.

This dissertation describes the implementation of several new experiments in the chemical engineering teaching laboratory at the University of Connecticut that were developed to showcase chemical engineering fundamentals in a context that more completely reflects modern chemical engineering. Several experiments themed around membrane desalination were developed to highlight the interplay between fluid mechanics and mass transport in these processes. A third membrane-based experiment shows how salinity gradients can be used to generate power, linking concepts relevant to process thermodynamics and efficiency. Another experiment uses a 3D printer to teach students design considerations for laminar flow reactors, drawing on theory relevant to reaction engineering, mass transport, and fluid mechanics. In addition to these new experiments, the class structure was altered using gamification, which incentivized students to participate in the class beyond simply performing experiments by

providing additional ways to engage with the course and with the experiments they were performing. Gamification elements have proven successful in other science, technology, engineering, and mathematics (STEM) classrooms, but had not previously been applied to a chemical engineering laboratory in open literature. The game method was iterated to incorporate elements of game mechanics, narrative, and character progression to further maintain student interest in the class. Similar game-based methods were also used to augment another experiment-based course: a new project-based first year design course. Ultimately, students reacted positively to these changes and participation in optional elements of the laboratory course has increased. To maximize the impact of this work, all experiments and teaching methods are designed to be easily disseminated and customizable to the needs of the instructor, and many experiments that originated as part of this work have been adopted at other institutions.

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Enhancing Student Engagement and Learning in the Chemical Engineering Laboratory through Contextually Relevant Experiments & Novel Pedagogies

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CHAPTER 1

OVERVIEW

1.1 Motivation

The teaching laboratory is an essential part of undergraduate-level engineering education. Engineering by its very nature is practical, and laboratory courses are one of the only places in a common curriculum where students can physically interact with the material they are learning, allowing them to see first-hand the principles they are taught in their lecture courses. In a review article published in *Journal of Engineering Education*, Feisel and Rosa outline thirteen fundamental objectives of engineering instructional laboratories, shown below (2005):

1. **Instrumentation:** Students will learn how to apply instrumentation, sensors, etc. to make measurements.
2. **Models:** Students will learn how to critically assess how theoretical models can be used to predict real-world data.
3. **Experimentation:** Students will learn to design, execute, and interpret experimental procedures.
4. **Data Analysis:** Students will demonstrate the ability to collect, analyze, interpret, and draw conclusions based on experimental data.
5. **Design:** Students will build, test, and troubleshoot a part, device, or process based on specific requirements.
6. **Learn from Failure:** Students will diagnose the causes of unsuccessful outcomes and provide a successful solution.
7. **Creativity:** Students will show appropriate levels of independent thought and show capability to solve real-world problems.

8. **Psychomotor:** Students will be competent in their selection and implementation of appropriate engineering tools.
9. **Safety:** Students will identify and work to minimize potential health, safety, and environmental hazards.
10. **Communication:** Students will communicate the results of their experiments both in writing and orally.
11. **Teamwork:** Students will work effectively in teams, assigning roles and monitoring progress to meet specific deadlines.
12. **Ethics in the Laboratory:** Students will report information objectively and act with integrity.
13. **Sensory Awareness:** Students will gather information from the laboratory to make sound judgments and conclusions.

Many of these elements, such as instrumentation, models, and experimentation, cannot be taught easily in other, lecture-based courses. However, laboratory courses are often challenging to maintain and update due to the associated costs and changing landscape of the respective field of study. These challenges further make it difficult for some of the previously mentioned fundamentals of the laboratory, such as design and creativity, as many aging experiments may be streamlined to a point where experiments feel like rote repetition of the work of previous groups. Furthermore, the rise in use of personal computers has aided these objectives by adding new modeling and data acquisition methods to teaching laboratories. Ideally, instructional laboratory curricula should be maintained to be as relevant as possible to the specific engineering discipline. The curriculum should not only reflect modern equipment and data recording methods, but should reflect aspects of the kind of work current practitioners of the discipline may be doing on a daily basis.

For this reason, chemical engineering laboratories can be challenging to keep up-to-date given the rapid growth of the field in the past century. While in the late 19th century, chemical

engineers were primarily concerned with the mass production of chemicals (Cohen, 1996), the field quickly expanded to encompass reaction engineering and separations (Kim, 2002). While modern chemical engineering still has a fundamental focus on chemical processes and separations, the field has grown to include biotechnology, sustainability, and materials synthesis and processing (Mihelcic *et al.,* 2003, Vogel & Todaro, 2014). Many students pursue chemical engineering degrees with the expressed purpose of working in those specific fields, and the inherent interest in these areas can help students become motivated in chemical engineering classes like the teaching laboratory (Anderson *et al.*, 1984, Fink, 1995, Hidi & Harackiewicz, 2000). As such, educators should strive to expose students to these new content areas while still teaching core chemical engineering concepts. Keeping a modern curriculum will produce students who are more likely to gain relevant jobs and meaningful post-graduate work.

Furthermore, the teaching of students continues to be complicated by naturally changing student attitudes toward learning, particularly in the current age. Modern students have not known a time without computers or the internet, and there is evidence to suggest that this environment has given rise to a so-called "information-age mindset" (Oblinger, 2003). Some summarize this cohort of students, often called Millennials or Generation NeXt, as entitled, cynical, stressed, and prone to instant gratification, yet they are also highly adaptable and constantly strive for excellence (Taylor, 2006). Students have unprecedented access to knowledge in the form of the internet, but are skeptical of reality due to the ease with which information on the internet can be altered or faked. Students are inundated with so much information that multitasking becomes a way of life. Generally, these students approach learning in a results-oriented, trial-and-error manner, as opposed to the logic-based, fact-gathering approach of previous generations. These students also tend to have a low tolerance for delays and generally have high expectations for services such as their college education. As such, students may not feel motivated to actively participate in traditionally taught classes unless the classes are perceived as engaging or fun (Mina & Gerdes, 2006).

These student attitudes present unique challenges to laboratory courses, as the attitudes and outlooks of the current generation of students may be contradictory to many of the objectives of an instructional laboratory. For instance, needing to troubleshoot a piece of equipment may frustrate a student who is simply looking for an accurate experimental outcome, making them unable to see that the troubleshooting process is itself a valuable learning experience. Other aspects such as experiments that students do not find inherently interesting or relevant or communicating with a team that a student does not particularly like may cause a student to further disengage from the laboratory course. Failure to engage these students on their own terms within the instructional laboratory context may result in otherwise capable engineers receiving a lower quality education, making them unprepared for the job market or for graduate-level study. These sociological trends are likely to increase as time goes on, with children gaining access to interactive electronics technology at even earlier ages (DeCurtis & Ferrer, 2011, Jones, 2011, Worthen, 2012).

These changing attitudes have manifested themselves in the way students approach the capstone Chemical Engineering Laboratory course at the University of Connecticut. Students have expressed anxiety over the coursework, apathy towards some of the older experiments, and an attitude that the laboratory course is something to be "endured" rather than an opportunity to apply what they have learned to a real scenario. These attitudes can detract from the students' understanding of course materials. These trends imply that changes are necessary to the way classes are taught to accurately reflect the changes in the field and within the student population. Changes must be made in order to attract the best students and to make sure they are adequately prepared for the current chemical engineering landscape upon graduation. Therefore, it is essential to provide an updated laboratory curriculum with experiments that are contextually relevant to modern chemical engineering. Moreover, the way the laboratory course is taught must be updated, allowing students new ways to actively engage with the material and core concepts presented in the experiments in a manner that is interesting

to them. Both of these tactics are expected to stimulate student interest in the laboratory, which will hopefully lead to students with a stronger laboratory-based background.

1.2 Objectives and Scope

The purpose of this work is to propose new avenues through which modern student engagement and learning can be promoted or enhanced within the chemical engineering laboratory course. It is anticipated that the emphasis on engagement will cause student attitudes toward the laboratory course to improve, which may promote more investment in the material and better retention of laboratory material (Shlomo & Tan, 2008). The experiments and systems created and discussed in this work are designed for easy dissemination, and an instructor may adapt or modify these methods to better fit any course that he or she deems appropriate. Adaptability is paramount in these designs to maximize their potential impact, as each university has different resources, course descriptions, and infrastructure. To further this goal, experiments developed as part of this work cover a large amount of chemical engineering topics, making them relevant to several core undergraduate courses.

It is hypothesized that to maximize the improvement in the attitudes of modern students toward the capstone laboratory course, both the experimental content presented in the course and the way the course is taught must be altered to better reflect contemporary chemical engineering and the way modern students learn. Game-based learning was chosen as the method to update the style with which the laboratory course is taught due to the popularity of games with modern students ("2014 Sales, Demographic, & Usage Data", 2015) and the efficacy of game-based education in other, non-engineering contexts (Kapp, 2012, Sitzmann, 2011, Ke, 2009, Vogel *et al.*, 2006, Hays, 2005, Randel *et al.*, 1992). Therefore, the objectives of this work can be categorized into two major categories: development of new chemical engineering experiment objectives and development of game-based learning objectives.

The objectives of the experimental design aspect of this work are as follows:

1) To design and implement several new experiments for the capstone chemical engineering course that demonstrate a wide array of chemical engineering phenomena (thermodynamics, fluid mechanics, heat transfer, mass transfer, reaction kinetics).
2) To create experiments that highlight the interplay between two or more of the content areas listed previously, allowing students to synthesize data from multiple classes and examine how different principles of chemical engineering interact with one another in an observable and measureable context.
3) To develop experiments that present these chemical engineering fundamentals in the context of a modern or emerging area of chemical engineering, such as membrane separations and additive manufacturing, to broaden student understanding of what chemical engineers do currently. Moreover, each experiment should present the material in a way that is novel to some extent, rather than simply repeating what is already available in open literature.
4) To assess student understanding of the material based on laboratory reports and use student feedback to improve each experiment, making sure that the experiments are promoting student understanding of the fundamental chemical engineering concepts.

The objectives for the game-based learning aspect of this work are as follows:

1) To develop a system for a game-based capstone laboratory using elements of gamification to encourage student participation, following the definitions of what constitutes a game.
2) To find a method to promote alternative and optional avenues for student engagement with the course material, regardless of student skill level, without trivializing or overshadowing the required course content. This method should allow

students to take a greater responsibility and role in their own education as they decide the optional aspects in which to participate.

3) To allow students to feel as though their individual or collective actions in the laboratory course have some aspect on the game, and ultimately to allow students to feel as though their actions influence the outcome of the game.
4) To monitor student participation in laboratory activities and assess their attitudes toward the laboratory course. Individual student performance, such as scores on written laboratory reports, will be compared when possible to establish links between participation in the game and student learning. Comparisons may be complicated given changes to the University of Connecticut chemical engineering curriculum during the course of the study.

Ultimately, the goal of this work is to create a meaningful laboratory environment in which students can become invested while still being taught essential chemical engineering concepts in ways they can see as relevant once they graduate and become practicing engineers.

1.3 Thesis Organization

The main body of this dissertation is divided into two sections. Each section begins with a chapter (Chapter 2 and Chapter 8) detailing background, context, and definitions relevant to all chapters of that section. Each individual chapter will contain background information, relevant equations, and methodology that pertains to the work presented in that chapter. Chapter 12 presents a summary of the work, a discussion of the contributions to chemical engineering and engineering education, and avenues for future work.

Section I is comprised of Chapter 2 through Chapter 7. These chapters discuss several experiments that were developed using modern chemical engineering technologies as a platform to teach students various fundamentals of chemical engineering. Chapter 3 outlines the design of a crossflow reverse osmosis system that allows students to alter hydrodymanic

conditions, allowing them to examine the link between mass transport and fluid mechanics through the context of pressure-driven water desalination. Chapter 4 describes a crossflow forward osmosis system designed to allow students to examine mass transport in the context of a membrane process that relies on osmotic potential as a driving force. These two chapters demonstrate how membrane desalination platforms can be used to illustrate subtle differences in mass transfer boundary layer formation when different types of forces are used to drive flux. Both of these experiments stress fundamentals of mass transfer to students, which is often a difficult subject for students to understand and visualize. Both of these chapters will include materials and methods required for these experiments, student-generated results, and student attitudes and feedback about the experiments.

Chapters 5 and 6 of Section I discuss two facets of a potential experiment themed around pressure retarded osmosis and osmotic power based on an experimental study of pressure retarded osmosis operating conditions. Chapter 5 introduces the concept of pressure retarded osmosis and the osmotic heat engine, a closed-loop process that can convert low quality energy into electricity. A membrane and osmotic pressure gradient are used to generate work, a hydroturbine harnesses that that work, and a stripper-absorber replenishes the concentrations of the working solutions as the osmotic potential decreases due to dilution. The most challenging aspect of this system is the stripper-absorber, which must recover draw solutes at low temperature. A falling-film stripper system in the context of the osmotic heat engine will be featured in Chapter 5. The stripper can serve as an illustration of heat transfer and thermodynamic equilibrium to students, and can provide contrast to the chemically driven gas absorption column that currently exists in the chemical engineering teaching laboratory at the University of Connecticut. However, as the system needs to be tested extensively with engine performance and safety in mind, a pressure retarded osmosis experiment can still be performed at the bench-scale to introduce the concept to students. While the bench scale system does not use a hydroturbine to generate power, students can still examine how

experimental conditions such as osmotic pressure gradient and temperature can impact power generated. Chapter 6 details a system and procedure that demonstrate how power can be generated from an osmotic pressure gradient using a membrane and how the amount of power generated is a strong function of solution osmotic pressure. With minimal modifications to the system presented in Chapter 4, the same procedure can be used as the basis for a laboratory experiment in pressure retarded osmosis, providing a link between thermodynamic work, mass transfer, and fluid mechanics.

Chapter 7 outlines the final experiment developed during this work, which is a reactor design experiment that allows students to design and print inexpensive laminar flow reactors using a 3D printer. This experiment is designed to build upon previous reaction kinetics experiments that students have performed. However, rather than manipulating variables such as flow rate to alter conversion, students are encouraged to fundamentally change the design of their reactor to increase conversion. The small scale of the reactors also forces students to perform reactions in the laminar flow regime, which most undergraduate kinetics courses do not cover. This experiment makes students aware of many limitations imposed when designing reactors that they may not be aware of if they are used to working primarily with turbulent flows. Furthermore, as students may not have been exposed to the complex math of laminar flow reactors, students use COMSOL Multiphysics to predict the conversion at various flow rates and compare the simulation to their experimental data. As such, this experiment teaches software packages such as COMSOL and Solidworks to students in addition to the kinetics and reactor design learning outcomes. This chapter will include student-generated results, both experimental and simulation.

Section II is comprised of Chapter 8 through Chapter 11. This section's primary theme is the use of gamification to enhance the way that the active learning courses are taught, providing students additional avenues to engage with the course material and with the way the course is being taught. Chapter 9 details the first implementation of a gamified extra credit

system in the senior-level chemical engineering laboratory course. This implementation used basic badge, point, and leaderboard (BPL) gamification, where students competed for points that could be earned by performing tasks that helped students improve their laboratory skills, encourage appropriate data analysis, or helped them to discover broader impacts of their experiments. While this attempt was moderately successful in garnering student interest, there was a desire to move beyond BPL gamification to more meaningful gamification. Therefore, Chapter 10 discusses a second iteration of the gamified laboratory, which introduced game mechanics, a narrative, and character creation elements to give students further avenues to engage with the material and practice collaboration and communication within groups. These chapters will discuss the methods for each implementation, as well as metrics of student participation, attitudes, and feedback. There are also attempts to use the limited sample size of students to find patterns between student participation in the game and student learning and performance.

Finally, Chapter 11 details the use of games in another course with active learning and laboratory elements. When the first-year engineering foundations course was converted from a traditional lecture course into a project-based course, a game system was added that was integral to the way the course functioned. Students were split into teams called companies and were given budgets of in-class currency that they used to purchase materials to complete design objectives. Student companies then entered their designs into a class competition, where they were judged on different metrics depending on the project. This chapter will provide details about how the course functions, feedback from the first implementation of these systems, and improvements that have been made for the second offering of this particular course.

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SECTION I

DEVELOPMENT OF CONTEXTUALLY RELEVANT EXPERIMENTAL MODULES

"All life is an experiment. The more experiments you make the better."
– Ralph Waldo Emerson

CHAPTER 2

EXPERIMENT DEVELOPMENT BACKGROUND

Prior to providing details about the experiments that were developed as part of this work, it is important to explain the context in which they were produced. This section will detail the experimental curriculum in the senior-level unit operations chemical engineering laboratory at the University of Connecticut both before and after a restructuring of the laboratory sequence in the junior and senior years. Topic areas of need are identified, followed by the methodology used to develop each of the experiments discussed in this section. Finally, some examples of other experiments implemented into the laboratory curriculum will be briefly discussed in the context of how they meet the experiment design criteria and what role they play in the context of the updated laboratory.

2.1 Previous Laboratory Curriculum

Prior to 2012, the senior chemical engineering laboratory course at the University of Connecticut was a two-semester, six-credit sequence that fulfilled all six credits of the university writing requirement. This sequence was comprised of nine experiments, summarized in Table 2.1. Students performed five experiments in the first semester and four experiments in the second semester. Most experiments lasted two four-hour laboratory periods, with the exception of distillation and evaporator, which lasted four four-hour laboratory periods. Student reports were in the form of written reports and oral presentations of varying length.

Table 2.1: List of experiments present in the 2008/2009 capstone chemical engineering laboratory course at the University of Connecticut

Experiment	Topics Covered
Gravity-drained Tank	Fluid mechanics
Bubble-Cap Distillation	Unit operations
Double Effect Evaporator	Unit operations
Carbon Dioxide Absorption	Unit operations
Pump & Pipes	Fluid mechanics
Heat Exchanger	Heat transfer
Batch & Continuous Reactors	Reaction kinetics
Biodiesel Kinetics	Reaction kinetics
Draining Tank Level Control	Process control

The context of these experiments is firmly rooted in classical chemical engineering concepts, predominantly highlighted by two pilot-scale thermally driven separation experiments in the form of the double-effect evaporator and distillation column. However, all experiments were aging and required several updates, including new computerized data acquisition methods to make the laboratory experience more modern. For example, both the distillation column and heat exchanger were updated with a computer interface to collect temperature data, replacing old toggle-based temperature outputs. Another example of improvements implemented during this time was the redesign of the continuous stirred tank reactor (CSTR) experiment, which was modified to allow students greater control over the liquid-level in the CSTR, increasing the accuracy of student results.

Students expressed concerns about the laboratory facilities and equipment frequently. Often, students would feel frustrated that they would need to perform a certain experiment when they did not plan to pursue a career in related fields. For instance, several students who had interest in biology questioned why they would need to learn to run a two-story distillation column. In post-course exit interviews, students frequently commented that relatively simple experiments like the pipe rack or heat exchanger would have been beneficial to perform during the junior year, when students take classes surrounding transport phenomena. The idea behind this change was the thought that performing these experiments would reinforce lecture material through experience. This change caters to different student learning styles; some students will

prefer the audial and visual elements of lectures while others will learn better through active engagement and hands-on experience (Felder & Silverman, 1988).

2.2 Reorganized Laboratory Curriculum

Responding to the student feedback, the Chemical and Biomolecular Engineering Department at the University of Connecticut removed three credits of laboratory from the senior year and distributed it in the junior year. A one-credit fluid mechanics laboratory was offered during the fall semester, which was followed by a two-credit transport & kinetics laboratory in the spring semester. The remaining three-credits of the senior laboratory course were offered both in the fall and spring semesters, allowing students to select which semester in which to take the capstone laboratory and enabling smaller class sizes to give students more exposure to the experiments and instructors. However, the senior laboratory would now only fulfill half of the university writing requirement.

In order to populate the junior-level laboratory courses with experiments, the more one-dimensional laboratories were removed from the senior-level laboratory. These experiments included the pump, the pipe rack, the heat exchanger, and the small-scale reaction kinetics experiments. The experiments for the restructured laboratory sequence is presented in Table 2.2. While the senior-level laboratory losing experiments necessitated the need to generate several new experiments to replace those that were moved, the new structure allowed for more experimentation with the laboratory schedule. Rather than three two-period experiments and one four-period experiment per semester, students were tasked to complete one two-period experiment, one four-period experiment, and one six-period experiment. This change required that students be in the laboratory for more laboratory periods than the previous structure and allowed students to perform more in-depth studies for certain experiments. The increased in-class time commitment was counterbalanced by students performing fewer experiments and, therefore, preparing less reports and presentations. In the previous laboratory curriculum, students prepared two individually written reports (15 to 30 pages each) and two individual oral

presentations per semester. In the new laboratory curriculum, students prepared one individually written report (~15 pages in length), a group oral presentation, and a group poster presentation.

Table 2.2: Experiments reorganized based on new laboratory structure

Fluid Mechanics Laboratory Experiments	Transport & Kinetics Laboratory Experiments	Senior Laboratory Experiments
Centrifugal Pump	Heat Exchanger	Double-effect Evaporator
Pipe Rack	Batch Reactor Kinetics	Bubble-cap Distillation
Draining Tank	CSTR Kinetics	Biodiesel Kinetics
		Carbon Dioxide Absorption
		Draining Tank Level Control

However, as the junior-level laboratories were being implemented, several of the remaining senior-level experiments were also necessarily brought offline. The biodiesel experiment was removed from the curriculum due to the shut down of the biodiesel laboratory. The evaporator was also removed at this time since leaks in the system and inaccurate flow meters did not allow students to accurately close mass or energy balances, severely limiting the learning opportunities available. The loss of these two experiments created a need to develop new experiments themed around reaction kinetics and/or large-scale separations. Furthermore, the experimental curriculum lacked a fundamental mass transport experiment. While the carbon dioxide absorption experiment does have mass transfer elements, the absorption is driven by a sodium hydroxide solution, and student results often indicate that the reaction kinetics overwhelm any mass transport effects imposed by gas or liquid flow (Tepe & Dodge, 1943). Additionally, the transport & kinetics laboratory course needed experiments to clearly demonstrate mass transport. In designing new experiments for the laboratory, the areas of separations, mass transport, and kinetics were prioritized to add to the breadth of the overall laboratory experience.

2.3 Experimental Design Approach

When designing the new experiments for the senior-level unit operations laboratory, two key criteria were used. By the first criterion, each experiment developed needed a clear link to

one or more core chemical engineering content areas. These areas could include fluid mechanics, thermodynamics, transport operations, reaction kinetics, and process control. Each experiment needed a clearly defined learning objective in the context of one of these core areas, as clear learning objectives would help guide the design of each experiment (Feisel & Rosa, 2005). In order to make the experience worthwhile for a senior in chemical engineering, it was preferable for at least two areas to be highlighted to demonstrate the links between different core concepts and to differentiate these experiments from the junior-level ones, which typically focused on only one area. However, an experiment that can be run to emphasize one content area at the junior-level and multiple when revisited at the senior-level, as doing so can help reinforce learning while promoting new learning, creating a minor spiral curriculum within the laboratory, where topics are revisited in subsequent courses with additional complexity (DiBiasio *et al.*, 1999). As stated in the previous section, the topic areas of mass transport and kinetics were given special priority, as the laboratory had traditionally lacked mass transport experiments and had recently lost a key kinetics experiment.

The second criterion stated that each newly developed experiment was to present the fundamentals in a context more reflective of areas now encompassed modern chemical engineering. These contexts may include biotechnology and pharmacy, sustainability and energy, materials and polymers, computer simulations of processes, and others. These contexts may make experiments more interesting to students who hope to be employed in these sectors or hope to do graduate research studying similar fields, addressing previous student comments questioning why certain experiments needed to be performed. This criterion justifies the importance of the first, as these fields may diverge from what is traditionally considered chemical engineering. While students may desire experiments of a certain theme, the core content areas must to be stressed to meet the objectives and standards of ABET or any external advisory boards.

In order to assess the effectiveness of the new experiments, observation of the students as they completed their experiments was critical. Observations included how students were approaching the new experiments and what questions student asked during the course of the experiment. Student report grades were also examined for concept understanding and appropriateness of data analysis. Students completed surveys at the conclusion of each experiment where they were asked to rate their level of interest, engagement, and learning from the experiment, or they were asked to assess various aspects of the experiment including previously existing background, data acquisition, and data analysis. For a baseline level of assessment, students were also asked to give their opinions on the previously existing experiments. This information was used to assure that the learning objectives for each experiment were are being met.

2.4 Examples of Other New Experiments

Several experiments were developed since 2009 using the criteria described in the previous section. While many are the focus of this section of the dissertation, there are a few others that merit mention here as illustrations of this methodology. The first is an initiated chemical vapor deposition experiment that teaches students about reaction kinetics and mass transport through the context of a gas-phase polymerization reaction (Burkey *et al.*, 2014). Gaseous acrylate monomers are initiated by a peroxide and deposit on a silicone wafer in a vacuum chamber. Students examine whether the rate of reaction or the rate of mass deposition have a stronger impact on the formation of a layer of polymer coating. At the time of its inception, this system was the first chemical vapor deposition experiment present in an undergraduate teaching laboratory nationwide. This system was also used to generate data for peer-reviewed papers on the potential of hexyl acrylate for photo-initiated chemical vapor deposition, shown in Figure 2.1 (Suresh *et al.*, 2014).

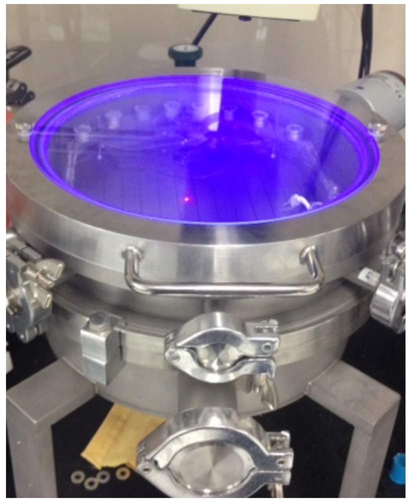

Figure 2.1: The reaction chamber of the chemical vapor deposition experiment during a photo-initiated deposition.

Another experiment developed during this period was an *E. coli* fermentation using a BioFlo 3000 bioreactor, shown in Figure 2.2, that was donated to the department by Alexion Pharmaceuticals. In this experiment, students culture samples of JM109 *E. coli* in the bioreactor and take samples in order to determine key biokinetic parameters such as the maximum growth rate and Monod constant (Healy, 1980, Shuler & Kargi, 2001). This experiment meets student demands for additional experiments based in biochemical engineering techniques while introducing them to a new model of kinetics based on the concentrations of the substrate and the growth of the *E. coli*. The experiment also trains students with respect to sampling and sanitation techniques as it uses a reactor that is used frequently in industrial applications.

Figure 2.2: Photograph of the BioFlo 3000 bioreactor used in the *E. coli* fermentation experiment.

Another biologically themed experiment is the drug delivery experiment based on the work of Farrell and Vernengo (2012). In this experiment, students use tartrazine as a simulated drug and measure the release rate from beads they create using alginate hydrogels into a beaker of water simulating the human body. Students can vary the alginate and tartrazine concentrations, beaker mixing rate, and crosslinking time and determine how these parameters influence the mechanics of dye release (Ritger & Peppas, 1987, Ritger & Peppas, 1987, Peppas & Sahlin, 1989). This experiment demonstrates how to use certain empirical correlations and teaches students about mass transport in the context of a problem that is relevant to both pharmaceuticals and materials science. The experiment is also a fundamental examination of mass transfer.

The final new experiment was adapted from a transient heat transfer experiment using beverage bottles proposed by Clark *et al.* (2010). This experiment's basis is in advertising claims that certain materials allow beverages to cool faster but stay colder for a longer period of time. To show this claim contradicts basic heat transfer theory, students cool plastic, aluminum,

and glass bottles in a refrigerator and in ice water, measuring the temperature using a computerized data acquisition software. Students then model each bottle in COMSOL Multiphysics to verify their observations, exposing the students to the modeling software and providing a relatively simple system for them to learn to model in the software. Thus, this experiment links heat transfer and computer simulation.

The junior- and senior-level laboratory experiment curricula as it is currently being run in the Fall 2014/Spring 2015 academic year are presented in Table 2.3, where experiments highlighted in green will be discussed at length in subsequent chapters. To display the growth of the laboratory in recent years, experiments that were present in the 2008/2009 laboratory curriculum are highlighted in purple. Note that the variety of experiments available during the senior year allow experiments to be grouped into sets of three, with each set containing at least one kinetics experiment, at least one mass transfer experiment, and at least one fluid mechanics or heat transfer experiment. These groupings allow students some degree of choice in what experiments they do, but they also ensure that all students are being exposed to the same core chemical engineering concepts. The experiment choice method has proven popular with students, who enjoy having some degree of choice in the experiments they perform.

Table 2.3: Current experimental curriculum for the Fall 2014/Spring 2015 academic year for the junior- and senior-level chemical engineering laboratory courses at the University of Connecticut; cells highlighted green will be discussed in detail in subsequent chapters, and cells highlighted in purple indicate experiments present during the Fall 2008/Spring 2009 academic year. Starred cells indicate that improvements were made to those experiments between Spring 2009 and Spring 2015

Fluid Mechanics Laboratory (Fall)	Transport & Kinetics Laboratory (Spring)	Senior Capstone Laboratory (Either)	Currently in Development or Temporarily Offline
Centrifugal Pump*	Heat Exchanger*	Chemical Vapor Deposition	Pressure Retarded Osmosis/Osmotic Heat Engine
Venturi Meter	Heat Conduction	3D Printed Laminar Flow Reactors	Activated Carbon Adsorption Column
Gravity-drained Tank*	Reverse Osmosis	Bioreactor Fermentation	Fluidized Bed
Fluid Flow in Pipes	Batch Reactor Kinetics	Reverse & Forward Osmosis	Bubble-Cap Distillation*
	CSTR Kinetics*	Drug Delivery	
		Carbon Dioxide Absorber*	
		Draining Tank Level Control	
		Transient Heat Transfer in Bottles	
		Coffee Brewing & Caffeine Leaching	

CHAPTER 3

TEACHING MASS TRANSPORT AND FLUID MECHANICS USING REVERSE OSMOSIS

Originally published as:
"Teaching mass transfer and filtration using crossflow reverse osmosis and nanofiltration: An experiment for the undergraduate unit operations laboratory"
by D. Anastasio and J. McCutcheon
in *CEE – Chemical Engineering Education* **46**(1) (2012)

3.1 Introduction

Fresh water is a limited resource. Less than 1% of water on the planet is fresh and easily accessible, and it is projected that, by 2050, one third of the global population will be without a secure source of clean drinking water. These circumstances have prompted research into techniques that augment the amount of available freshwater through water reuse and desalination. Membrane separations have become a popular method of desalination due to recent advancements in the field coupled with the relatively low energy requirement compared to thermally-driven desalination. With mass transfer, separations, and process engineering at the core of their curriculum, chemical engineers are uniquely suited to design optimized separation processes involving membranes if they are given the opportunity to learn about their operation. It is therefore imperative that we integrate membrane separations into the undergraduate chemical engineering (CHEG) curriculum to prepare our students to tackle these grand challenges with new technologies.

In all ABET accredited chemical engineering programs, a laboratory course is required to provide hands-on experience to students who have completed their core CHEG coursework. Many CHEG programs, including the Chemical, Materials, and Biochemical Engineering (CMBE) department at the University of Connecticut (UCONN), have been updating their laboratory curricula to more accurately represent modern technologies. The undergraduate CHEG Laboratory at UCONN contains only two separations experiments: a pilot-scale double-effect evaporator and a 20-stage distillation column. These thermal separation methods have

value as classical chemical engineering approaches. However, these techniques are becoming obsolete in certain sectors of industry. Modern employers demand knowledge of newer separation methods from recent graduates. As membrane separations become more commonly employed, students require practical experience with a system that teaches key membrane separations concepts while reinforcing mass transport fundamentals. For this reason, a membranes separations experimental module was created for the CHEG Laboratory course at UCONN. One component of this module is a crossflow reverse osmosis (RO) system.

Previously published studies on RO experimental development have often described dead-end filtration type systems (Moor *et al.*, 2003, Mohammad, 2000). These systems operate in a batch mode, using a pressure vessel (sometimes stirred) to force water through the membrane. Dead-end filtration systems lack the ability to tightly control hydrodynamics, temperature and water recovery and are also subject to more serious concentration polarization. Other RO experiments employ commercial crossflow membrane modules (Slater, 1994). However, it is often difficult and costly to change the membranes in these systems, limiting the variety of membranes that can be tested. The system described in this paper is a crossflow RO system designed to mimic the conditions of an industrial membrane module while permitting a wide array of controllable variables. This system allows the students to observe change in membrane performance with changing hydrodynamic and fluid characteristics.

This experiment seeks to introduce students to vital membrane performance parameters: permeability and selectivity. Sometimes referred to collectively as permselectivity, these parameters are used to appropriately select a membrane for any particular separation challenge. Though this experiment focuses primarily on desalination, an understanding of these key performance metrics cuts across separation disciplines and applies to any liquid, gas or biological separation.

During the experiment, students will calculate the hydraulic permeability and salt rejection of several commercial RO or nanofiltration (NF) membranes and compare their values

to the manufacturer's specifications. This experiment is also designed to reinforce mass transfer boundary layer theory through an examination of concentration polarization (CP). Students will learn about the complex interplay between salt rejection, flux, and CP and think critically about possible applications for each membrane, considering each one's permeability and selectivity. The students will be asked to defend their conclusion, forcing them to think critically about the key design factors in RO desalination (feed water quality, product water quality and quantity, and operating pressure/power requirement).

The system described in this paper was designed to be mobile, robust, and easy-to-use. Test cells were designed such that small, single-use membrane coupons can be changed quickly between tests to permit the evaluation of multiple types of membranes. Furthermore, given the length of an individual test, multiple cells in series were needed to ensure data reproducibility, permitting students to obtain three flux measurements for every pressure they test and expediting the generation of data. Due to the relatively short channel length, pressure drop across each cell is negligible. Finally, the system was mounted to a modified cart to allow demonstrations outside of the undergraduate laboratory. This system has been used for demonstrations to the Membrane Separations class at UCONN and to visiting high school students as part of UCONN's Exploring Engineering (E^2) summer program. While a cart-mounted system has this added benefit, it is not essential to the functionality of this system.

3.2 Experimental Overview

A diagram of the cart-mounted RO system layout is presented in Figure 1. Pre-cut, pre-wet commercial membrane coupons are sealed into each of the test cells, and the feed tank is filled with deionized (DI) or saline water. After a brief equilibration period (30 minutes) at high pressure, students measure permeate flow rate and conductivity. This process was repeated at multiple pressures for pure water and at multiple flow rates for saline water. Using this data, hydraulic permeability (*A*) and salt rejection (*%R*) are determined for each tested membrane.

Boundary layer phenomena are also considered. The results are compared to the manufacturer's published specifications.

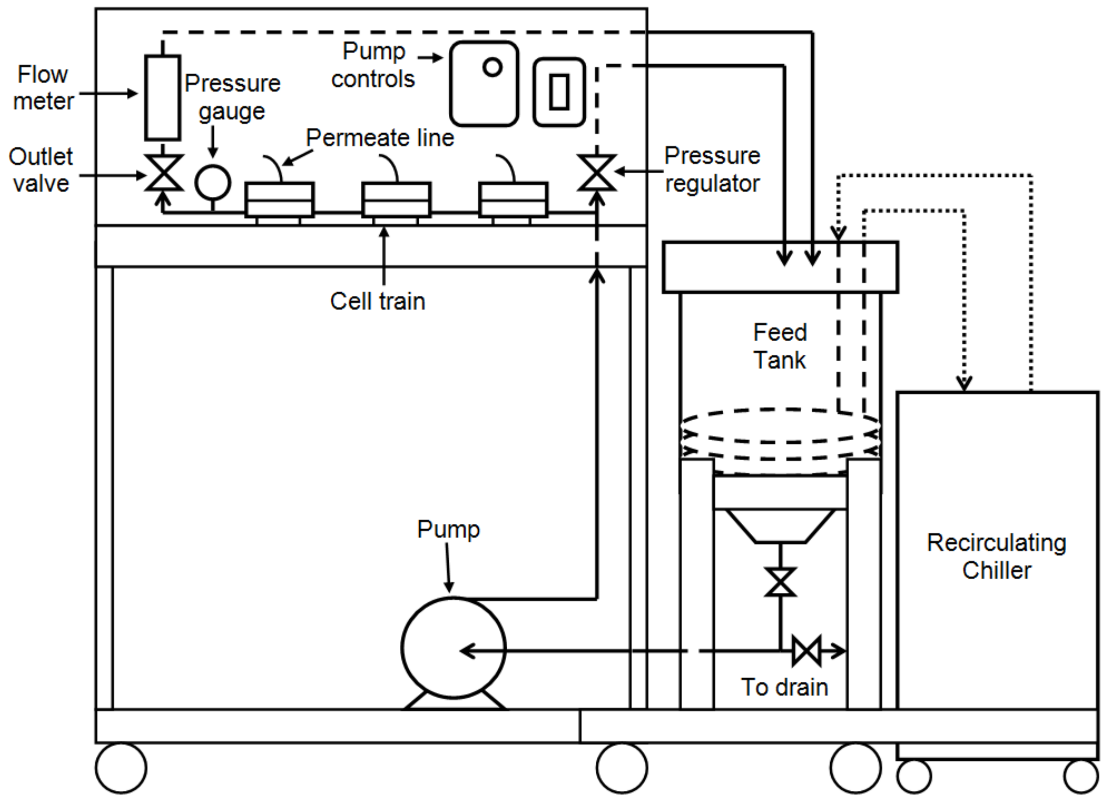

Figure 3.1: Schematic flow diagram of the crossflow reverse osmosis system.

Students are typically able to perform hydraulic permeability and salt rejection tests in approximately two hours for a NF membrane and three hours for a brackish water (BW) RO membrane. The length of this experiment can be extended by introducing more independent variables or different membranes. Prior to the experiment at UCONN, students read an instructional manual (Anastasio, 2015) and meet with a teaching assistant for system operation guidance. The RO system, as described, allows for control of many independent variables beyond membrane type and operating pressure, including crossflow rate, solute type, solute concentration and temperature.

3.3 Required Equipment

3.3.1 Membrane Selection

Flat sheet membranes have been graciously provided by Dow Water & Process Solutions for this experiment. Specifically, the BW30, NF90, and NF270 membranes were selected to provide students a wide range of membrane permselectivity (FILMTEC, 2012, “Dow FILMTEC NF270-400”, 2010, “Dow FILMTEC NF90-400”, 2010, “Dow FILMTEC BW30-400”, 2010). Dow’s seawater (SW) membranes could be used as well, but the low hydraulic permeability makes tests prohibitively long at the pressures tested with this system (up to 400 psi). RO membranes from other manufacturers are also appropriate. This experiment requires only small membrane coupons (approx. 8 in^2 per cell) that can be discarded after use.

3.3.2 Cell Design

The membrane cells are each composed of two halves fabricated from black delrin supported with stainless steel plates. The bottom half contains a crossflow channel, with dimensions 3” long by 1” wide by 1/8” deep, fed via threaded ports drilled into the sides of each cell. Surrounding the channel is a Viton O-ring (3” OD, 1/8” thick, McMaster) seated in a groove, which serves to seal the cell and prevent leaking. The top of the cell houses permeate collector that prevents damage to the membrane at high pressure. This collector is made of sintered stainless steel from Mott (Farmington, CT). The collected permeate flows through a 1/8” threaded fitting inserted into the top of each cell. These fittings are connected to lengths of flexible PVC tubing for easy collection. The two halves are placed on threaded stainless steel rods that are mounted to a stainless steel base plate, which can easily be affixed to a cart. Washers and nuts are used to support and seal the cell. Photographs of a sample cell are included as Figure 2. Detailed cell schematics are available upon request. If fabrication facilities are unavailable, pre-made cells with a similar design can be purchased from Sterlitech, General Electric, or Separation Systems Technology.

(a)

(b)

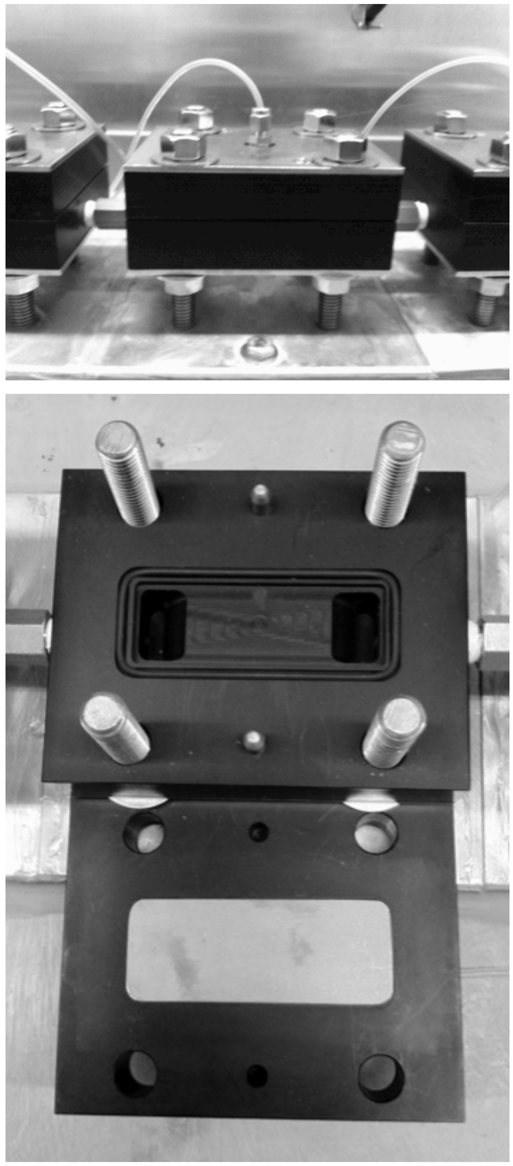

Figure 3.2: Photograph of reverse osmosis test cell (a) when closed, (b) when opened. The open cell shows the feed channel (top) and the permeate collector (bottom). This permeate collector is a sintered stainless steel plate (Mott Corporation).

3.3.3 Key System Components

The feed tank selected was a 5-gal Easy Drain cylindrical tank with stand from McMaster-Carr (Princeton, NJ). Reinforced PVC tubing joins the feed tank to the Multi-Speed Diaphragm Pump purchased from Wanner Engineering (Minneapolis, MN). A drain is installed in this line to facilitate system cleaning. The pump drive is equipped with a variable speed

controller that regulates the pump diaphragm frequency. The variable speed pump permits tests in the RO, NF, and ultrafiltration (UF) pressure regimes (though only NF and RO regimes are tested during this experiment). A high-pressure stainless steel braided hose (McMaster) connects the pump outlet to a stainless steel tee through the surface of the cart. This tee is connected to the first cell. System pressure and fluid flow rate are regulated by a pair of valves. The first is a front pressure regulator (50-500 psi, Wanner), which is installed on the aforementioned tee directly before the cell train and functions as a bypass valve. The second valve is a Swagelok SS-4L2 metering valve (Connecticut Valve and Fitting Co., Norwalk, CT), which regulates the flow of liquid that leaves the cell train. The effluent from this valve flows through a panel-mountable flow meter (0-1 gpm, McMaster). Liquid leaving the bypass regulator and flow meter are returned to the tank via tubing joined with quick-disconnect fittings to permit easy system flushing. A glycerin-filled pressure gauge (0-400 psi, McMaster) is installed between the membrane train and outlet valve. Figure 3 is a photograph of the membrane train with the two valves labeled. These valves are essential to optimal function of this system as they allow pressure and flow rate to be manipulated independently. An air purge port was also installed to allow the user to purge the system of residual water after cleaning. Filtered air is recommended to prevent oil or other particulates from contaminating the system. System temperature is maintained using a Neslab ThermoFlex 1400 recirculating chiller (Fisher) that has been integrated into the system through a coiled length of 316 stainless steel tubing that resides in the feed tank. The recirculator ensures temperature consistency by dissipating any heat generated by the pump during operation.

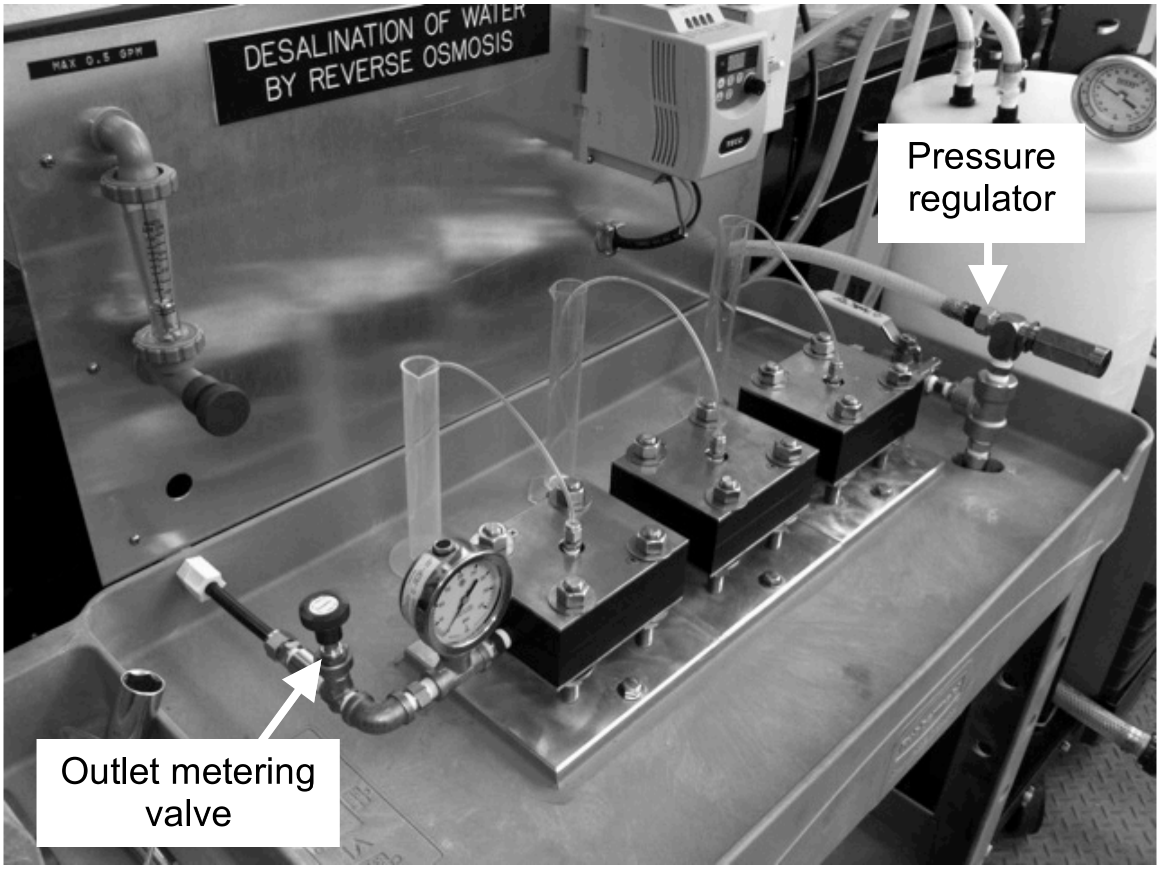

Figure 3.3: Membrane cell train with bypass pressure regulator and outlet valve labeled.

When selecting piping, tubing, and other fittings for the RO system, it is critical that all wetted parts resist corrosion, which could foul membranes and result in leaks. All pressurized components of the system (from the pump to the outlet valves and pressure regulator) should be plumbed using 316 stainless steel fittings and pipe. Any low-pressure areas may be plumbed using nylon or PVC fittings and hose. All major plumbing components (pipe, tubing, and fittings) were purchased from McMaster-Carr, unless otherwise specified. All components were all mounted directly to a Rubbermaid cart (McMaster) that had been modified with an aluminum backsplash and angle iron tank stand. Table 1 describes the estimated cost of system components.

Table 3.1: Estimated cost of system components

Component	Supplier	Approx. Cost
Recirculating chiller	Fisher Scientific	$3,000
Pump & controller	Wanner Engineering	$2,500
Three test cells	Custom	$1,500
Cart & tank	McMaster	$250
Meters & gauges	McMaster	$200
Valves	Swagelock, Wanner	$350
Tubing & piping	McMaster	$600
Conductivity probe	Fisher Scientific	$600
Total		**$9,000**

3.3.4 Measurement Devices

Permeate is collected directly into 50 mL graduated cylinders (McMaster). The cylinders allow data to be recorded quickly and easily. A stopwatch is used to measure the collection times. When a saline feed is used, the conductivity of the feed and permeate, which correlates to salt concentration, is measured using an Oakton Conductivity Probe (Fisher). The probe must be calibrated to measure concentration of the selected solute, which is accomplished by testing the conductivity of a serial dilution of a 2000 ppm stock solution of sodium chloride or other salt. A long-stemmed dial thermometer (McMaster) is inserted into the feed tank to monitor feed temperature.

3.4 Experimental Procedure

Before an experiment, a membrane sheet was cut into coupons that fit within the cell and completely cover the o-ring. Gloves were worn whenever membranes were handled as to minimize damage. RO membranes shipped from Dow are coated with glycerin, which acts as a humectant to prevent drying. The membranes were stored in DI water for at least 24 hours to remove residual glycerin. For longer term storage, membranes must be kept in a refrigerator to prevent bacterial growth. Two liters of 5-M sodium chloride stock solution were prepared for use as a salinity adjuster during the test. Since the system is pressurized, safety glasses should be worn during operation.

To begin a test, the feed tank was filled with 6 L of DI water, though more water may be needed depending on system hold-up volume. While wearing gloves, membranes were loaded and sealed into each cell with the selective layer facing downward toward the open channel. The chiller was set to 25 °C, in accordance to Dow's published test parameters. This set point may require modification to offset heat generated by the pump and ambient temperature. The pump was activated to purge air from the lines. After a few minutes, the system was pressurized by gradually closing the bypass regulator and outlet valve, alternating valves until the pressure is 300 psi. The system was equilibrated at this pressure for 30 minutes to flush air from the permeate tubes while compressing the membranes to provide uniform hydraulic resistance throughout the test. Longer equilibration times are acceptable but not practical within a laboratory period. After the equilibration period, permeate from each cell was collected in the graduated cylinders over a period of time at a desired pressure. Pressures between 100 and 300 psi are recommended, though students were encouraged to measure flux at the manufacturer's test conditions (70 psi for Dow's NF membranes, 225 psi for Dow's BW membranes). To optimize time spent in the laboratory, only 10 to 20 mL of permeate were collected per cell per pressure and all permeate was returned to the feed tank after volume was recorded. Once permeate flow rates had been observed for 3 to 5 pressures, the feed concentration was increased to 2000 ppm by adding stock solution (41 mL of 5-M sodium chloride stock for a 6-L DI water feed). Using stock solution is important since it rapidly mixes in water relative to the dissolution of solid salt. After a brief mixing period, pressure was maintained at the manufacturer's test specification while crossflow rate varied from 0.1 to 0.5 gpm. When testing salt rejection at each new flow condition, students should wait a few minutes for the fluid in the permeate line to flush out. A sufficient amount of permeate should then be collected in order to measure the conductivity accurately, but total permeate volume should be minimized so that the experiment does not take too long. Once permeate volume and collection time were recorded, permeate and feed solution conductivity were measured, and all permeate

samples are returned to the feed. This procedure should be repeated for at least three flow rates. Measurements should be repeated if time allows. Typical testing conditions for experiments performed by students at UCONN are summarized in Table 2.

Table 3.2: Typical operating conditions for RO experiments at UCONN

Variable	Typical Value/Range
Temperature	25 ºC
Initial feed volume	6 L DI water
High-pressure equilibration time	30 min
Feed concentration	0 ppm NaCl, 2000 ppm NaCl
Hydraulic pressure	0 – 300 psi
Hydraulic flow rate	0.1 – 0.5 L/min

Once all desired data was gathered, the tank was drained and refilled with DI water. The bypass and outlet return lines were disconnected and placed in a sink or a bucket with the outlet valve and pressure regulator bypass opened fully. The pump is then set to sufficient speed such that the flow rate is above 0.5 gpm. The tank is refilled with DI water as needed until the effluent conductivity was below 10 microsiemens (μS). If DI water is in short supply, a pre-rinse using tap water may be performed before a polishing DI water rinse. Flushing usually requires approximately 2 gal of water. The system was then purged with filtered compressed air to remove residual water. The cells were opened and the membranes removed to be examined for defects. If another test was to be immediately done, new membrane coupons were inserted and the procedure was repeated.

Due to the system's versatility, there are numerous other independent variables for students to explore if time permits. For pure water or saline water, students can explore the impact of temperature on flux and salt rejection. Temperatures can range from 15 to 35 °C. For saline water tests, the effect of solute concentration and solute type on observed salt rejection and CP can be examined. Other recommended solutes include magnesium sulfate and calcium chloride. Crossflow rate can also be held constant during salt rejection tests, varying pressure to increase and decrease flux. Furthermore, other commercial membranes can be tested.

3.5 Typical Results and Discussion

The relevant variables that differentiate RO membranes are hydraulic permeability (*A*) and salt rejection (*%R*). Salt permeability coefficient (B) can be used instead of *%R*, though rejection is generally a more pragmatic performance metric. In order to facilitate student analysis, it can be assumed that the feed solution is dilute. Therefore, the feed is an ideal solution with density and viscosity equivalent to that of pure water. Solute diffusivity can be approximated using the Nernst-Haskell equation (Geankoplis, 2003). The solution properties do not change appreciably during the test since the system is run at near 0% recovery since only 10-20 ml of permeate is collected from 6 liters of feed and all permeate is returned to the feed tank after each measurement. For a thorough overview of RO theory and calculations, refer to the textbooks of Mulder (1996) and Baker (2004).

Flux is determined by normalizing the measured volumetric flow rate of permeate by the surface area of the membrane. Flux is typically reported in gallons per square foot per day (gfd) or liters per square meter per hour (lmh). Once fluxes have been determined for each cell at a given pressure, students will average the three flux values and calculate the standard deviation. Using these average fluxes and standard deviations, pure water flux is plotted versus operating pressure in accordance with the generalized flux equation below:

$$J_w = A(\Delta P - \Delta \pi) \qquad (3.1)$$

where J_w, is water flux, *A* is the hydraulic permeability constant, ΔP is the transmembrane hydraulic pressure, and $\Delta \pi$ is the transmembrane osmotic pressure. As permeate pressure is atmospheric, ΔP equals the gauge system operating pressure, and $\Delta \pi$ is zero for pure water feeds. Figure 4 presents a summary of pure water flux data gathered by several groups of students using this system, presented with linear trend lines and standard deviation error bars. Note that students should report the units of *A*, the slopes of these lines, in either gfd/psi or

lmh/bar. This portion of the experimental analysis teaches students that, in general, NF membranes (NF270 and NF90) are more permeable than RO membranes (BW30).

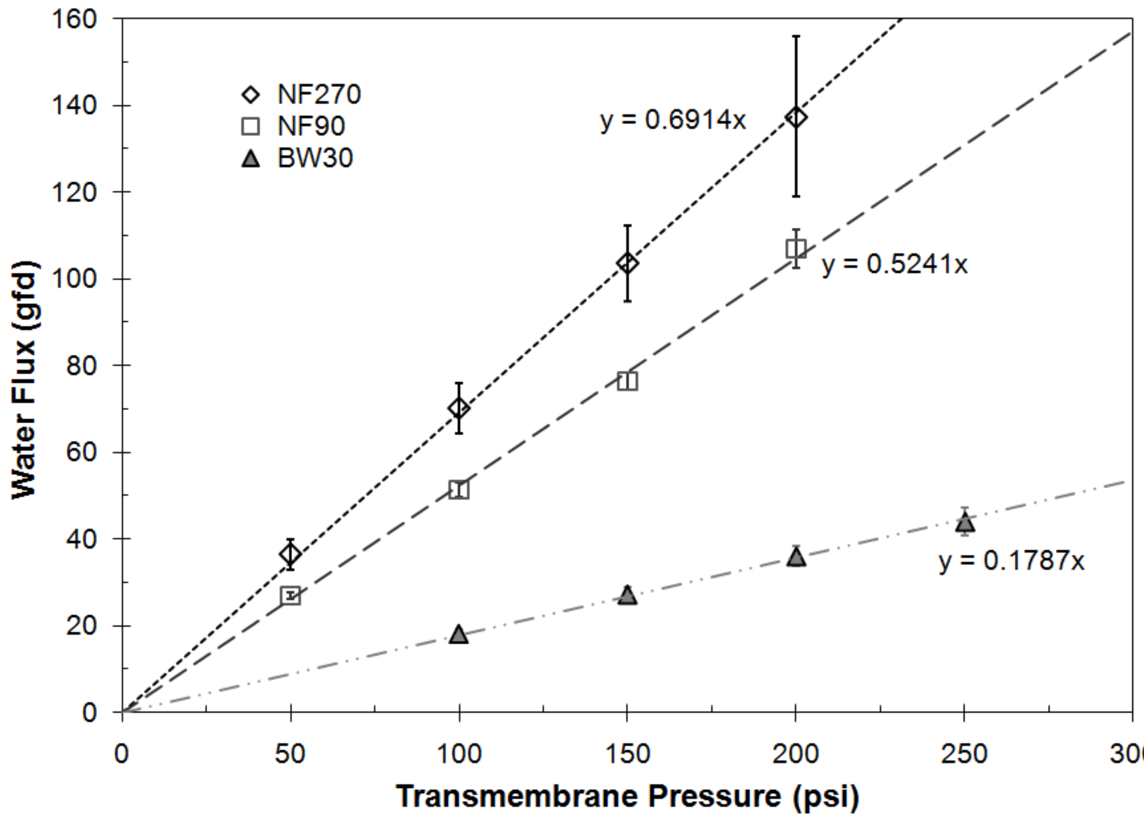

Figure 3.4: Pure water flux versus pressure for various NF and RO membranes from Dow Water & Process Solutions. Trend line slopes correspond to hydraulic permeability, *A*. Error bars indicate ± one standard deviation. All tests conducted at 25 °C. Note that 1 gfd is approximately 1.7 L/m^2.hr.

When a solute is present in the feed, the $\Delta\pi$ term in equation 1 is not zero. Furthermore, due to boundary layer effects, the osmotic pressure of the feed solution changes near the membrane interface. This phenomenon, illustrated in Figure 3.5, is known as concentration polarization (CP). Salts that are rejected by the membrane accumulate near the membrane surface while gradually diffusing back into the bulk solution. The relative rates of convection and diffusion dictate concentration of solute at the membrane interface. As a result, a steady state concentration gradient is established in which a bulk feed concentration, C_b, and a feed-side membrane interface concentration, C_m, are specified. For a thorough explanation of CP,

refer to the review paper written by Sablani *et al* (2001). A simple mass balance for flow of salt into and out of the boundary layer can be integrated into the following form:

$$\frac{C_m - C_p}{C_b - C_p} = \exp\left(\frac{J_w}{k}\right) \tag{3.2}$$

where C_p is the concentration of solute in the permeate and k is the mass transfer coefficient which, according to film theory, is equal to molecular diffusivity divided by boundary layer thickness. The mass transfer coefficient can be determined using Sherwood number (Sh = kd_h/D) correlations available from a variety of sources (Geankoplis, 2003, Cussler, 2009). The empirical Sherwood correlations presented to students in this experiment were provided by Mulder (1996) for both laminar and turbulent flow in a channel, presented below:

$$\mathrm{Sh}_{laminar} = 1.85(\mathrm{Re}\cdot\mathrm{Sc}\cdot d_h/L) \tag{3.3}$$

$$\mathrm{Sh}_{turbulent} = 0.04(\mathrm{Re}^{0.75}\cdot\mathrm{Sc}^{0.33}) \tag{3.4}$$

where Re is the Reynolds number, Sc is the Schmidt number, d_h is the hydraulic diameter of the channel, and L is the channel length. For the flow rates mentioned previously, the system usually operates in transition flow, and the results of the two Sherwood correlations are averaged. Once C_m is known, CP modulus (C_m/C_b) can be reported; for RO, the CP modulus is always greater than 1. The osmotic pressures of the permeate solution, bulk feed solution, and feed solution at the membrane interface can now be calculated using the idealized van't Hoff equation, shown below:

$$\pi = iCRT \tag{3.5}$$

where i is the moles of ions produced by the dissolution of one mole of the solute, C is the molar solute concentration, R is the gas constant, and T is the temperature. This equation, which indicates a linear relationship between concentration and osmotic pressure, is valid for dilute solutions. Thus, for relatively dilute solutions, the C_m, C_b, and C_p terms in equation 3.2 can be replaced with π_m, π_b, and π_p, the osmotic pressures of the solution at the feed-side membrane interface, bulk feed, and permeate, respectively.

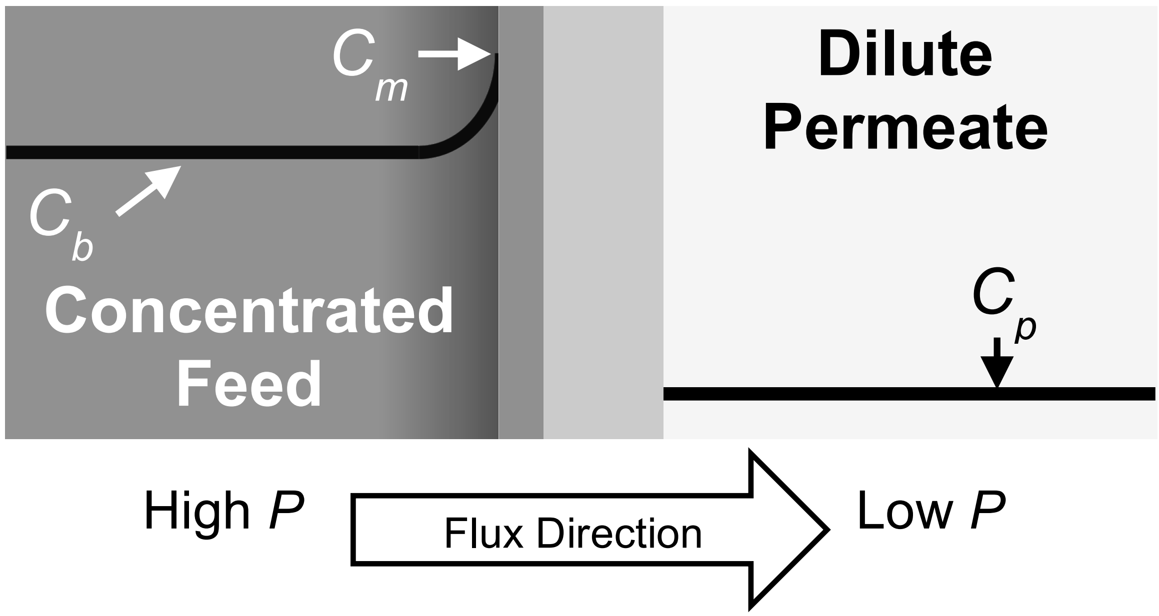

Figure 3.5: Illustration of concentration polarization. The black line indicates the concentration of solute in solution.

During experimental analysis, students can be asked to ensure that the water permeability constant is the same for the pure water and saline feeds. To use Equation 3.1, however, the students cannot use the observed osmotic pressure gradient ($\Delta\pi_{obs} = \pi_b - \pi_p$) to accurately evaluate A, as the term does not account for CP effects. Therefore, only the effective osmotic pressure gradient ($\Delta\pi_{eff} = \pi_m - \pi_p$) should be considered. When plotting flux versus driving force ($\Delta P - \Delta\pi_{eff}$), the data should be linear with a slope equal to the hydraulic permeability constant (A) and an x-intercept at zero, similar to the pure water test results. Table 3 compares typical A values calculated based on pure water tests, saline water tests, and Dow's published performance values. Students should be able to observe that A values do not appreciably change in the presence of salt. Discrepancies can be attributed to minor performance differences between individual membrane coupons.

Table 3.3: Experimentally observed hydraulic permeability (*A*) and manufacturer's reported *A* value range

Membrane Name	Experimental *A* value pure water	Experimental *A* value range, 2000 ppm NaCl	Manufacturer's *A* *value* range
	(gfd/psi)	(gfd/psi)	(gfd/psi)
NF270	0.82	0.82 – 1.02	0.45 – 0.72
NF90	0.43	0.44 – 0.52	0.36 – 0.58
BW30	0.18	0.17 – 0.19	0.12 – 0.13

A more advanced analytical method is flux prediction, which combines equations 3.1, 3.2, and 3.5 as follows:

$$J_w = A\left[\Delta P - \left(\pi_m - \pi_p\right)\right] \qquad \text{(from Eq. 3.1)}$$

$$\pi_m - \pi_p = \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right) \qquad \text{(from Eq. 3.2 \& 3.5)}$$

$$J_w = A\left[\Delta P - \left(\pi_b - \pi_p\right)\exp\left(\frac{J_w}{k}\right)\right] \qquad (3.6)$$

Equation 3.6, which is a nonlinear algebraic equation, can then be solved for water flux, J_w, using the experimentally observed feed concentration and hydraulic pressure along with the previously determined pure water permeability constant and mass transfer coefficient. Figure 3.6 is a parity plot of observed saline water feed flux data versus water flux predicted by boundary layer theory at various crossflow rates and constant pressure. The film theory model fits the data well for these membranes. This portion of the analysis is an excellent demonstration of key aspects of boundary layer theory. If flow rate is varied during a saline water test, mass transfer coefficient will increase with Reynolds number, resulting in a thinner boundary layer, lower CP modulus, and increased flux and rejection. If pressure is increased at constant crossflow rate, it is expected the boundary layer will grow as flux is increased and salt is forced against the membrane, increasing CP modulus and lowering observed salt rejection. The analysis also permits students to check the accuracy of their data against film theory and

published data, forcing them to critically consider sources of error, such as erroneous assumptions, data misinterpretation or poor data acquisition techniques.

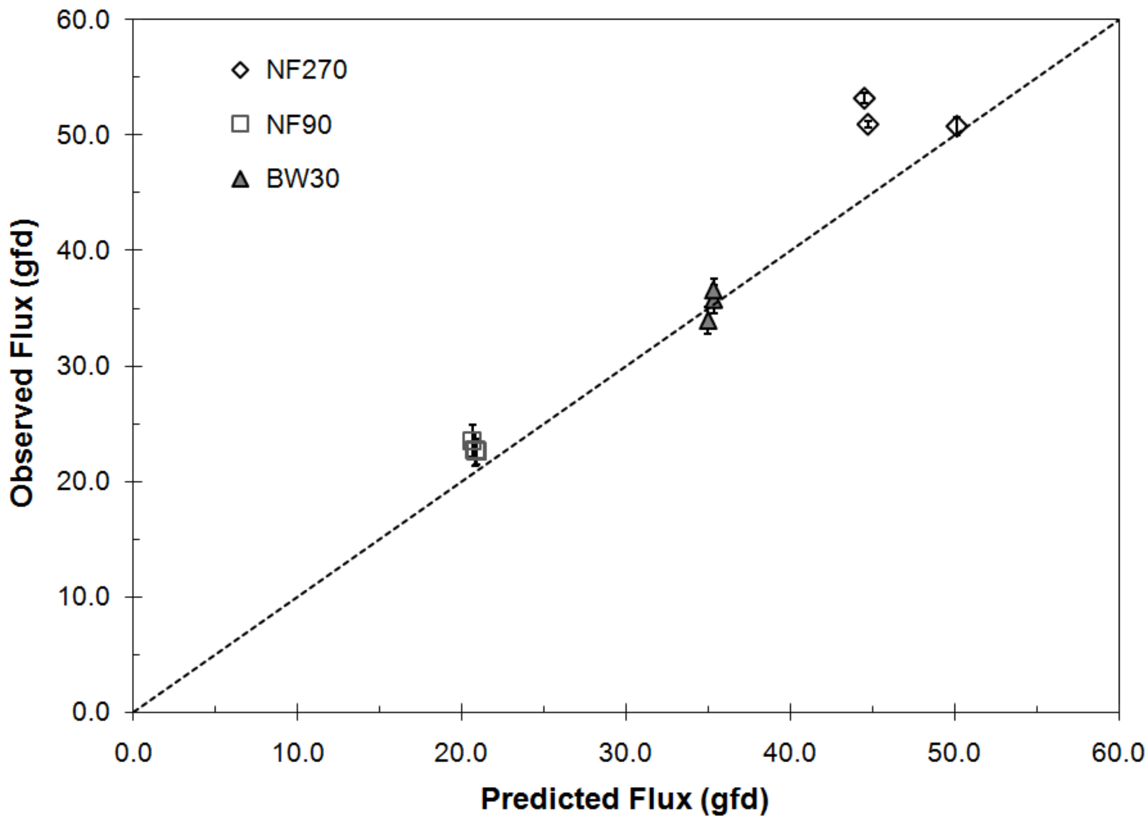

Figure 3.6: Parity plot of experimentally observed water flux and water flux predicted by film theory model with 2000 ppm NaCl feed at various crossflow rates. NF membranes evaluated at 70 psi, and BW membrane was evaluated at 225 psi. Error bars indicate one standard deviation. Note that 1 gfd is approximately 1.7 L/m^2 h.

The second key membrane performance metric is selectivity, often reported as observed percent salt rejection (*%R*) for RO. Rejection, the percentage of feed solute retained by the membrane, can be calculated using the following equation:

$$\%R = \left(1 - \frac{C_p}{C_b}\right) \times 100\% \tag{3.7}$$

An additional means of quantifying selectivity is the calculation of intrinsic salt rejection ($\%R_{int}$), which accounts for concentration of solute at the membrane interface. This rejection value can be calculated as follows:

$$\%R_{\text{int}} = \left(1 - \frac{C_p}{C_m}\right) \times 100\% \tag{3.8}$$

These rejections are compared to those published by Dow, accounting for the manufacturer's error limits, shown in Figure 3.7. The intrinsic rejection values are always greater than the observed rejection values, as the calculation accounts for CP effects and provides a more accurate measure of how much salt a membrane is capable of retaining. The observed rejection results are slightly lower than the published values, likely due to microscale defects that unavoidably form as membranes are shipped, cut, and loaded into the system. Minor defects may also form near the o-ring seals. The results are, however, within the limits of acceptable error as reported by Dow. This aspect of the experiment demonstrates the trade-off between membrane permeability and selectivity. The most permeable membrane, the NF270, also has the poorest salt rejection. The inverse is true of the BW30, the least permeable membrane. Understanding this relationship is essential when selecting membranes for an RO process and is a critical aspect of understanding membrane separations.

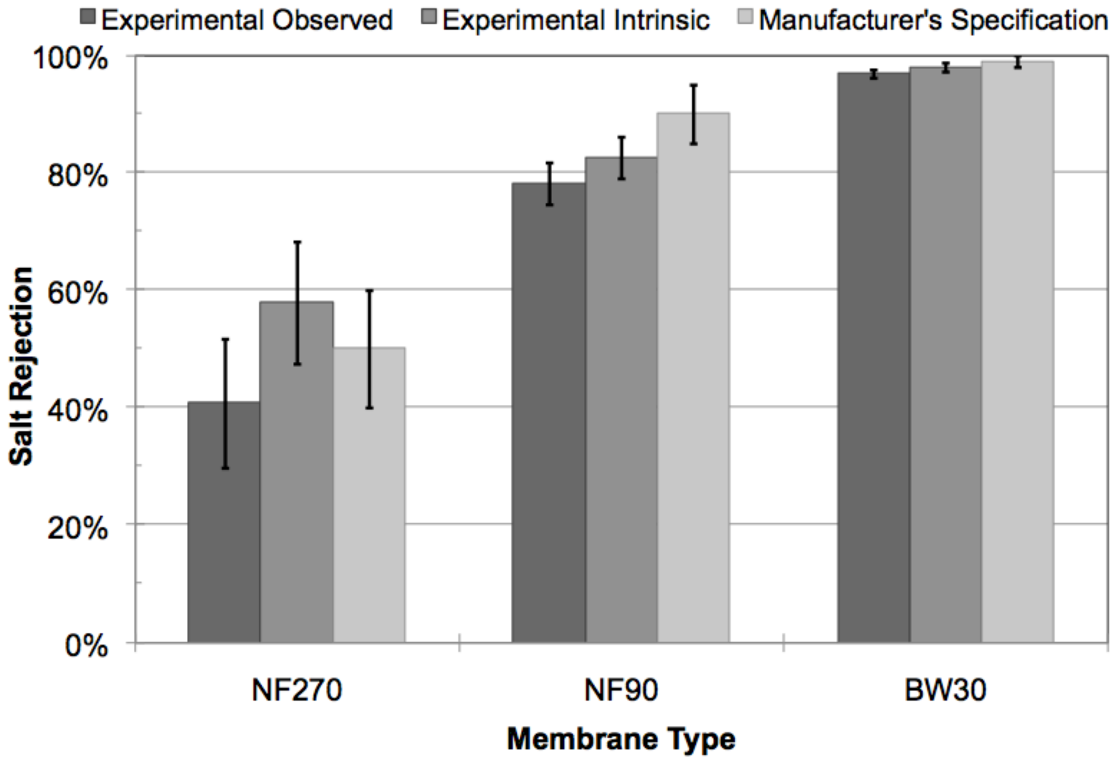

Figure 3.7: Observed and intrinsic salt rejection of various membranes based on student observations and values reported by the manufacturer. The feed solution was 2000 ppm NaCl. Error bars indicate one standard deviation.

All data presented in this manuscript was generated by senior-level chemical engineering students using the experimental apparatus as a part of the CHEG laboratory curriculum. Students were expected to obtain accurate hydraulic permeability constants and salt rejection values for each membrane while generating reasonable CP moduli. They will observe the trade-off between selectivity and permeability and determine the impact of operating conditions, such as pressure and flow rate, on overall membrane performance. Based on written and oral lab reports, the majority of students who performed this experiment were able to meet these goals. Some of the first student groups to use the equipment cited cell leakage as a possible source of error. Placing thicker o-rings in the cells remedied this problem.

The versatility of this system has enabled its use outside of the unit operations laboratory. We have used this system to provide a brief introduction to membrane separations

as part of UCONN's Exploring Engineering (E^2) Summer Program, which is aimed at teaching rising high school juniors and seniors about various facets of engineering. Using food coloring instead of sodium chloride in the feed, the system was used to introduce the students to basic membrane separations while teaching them the value of making assumptions (in this case, that osmotic pressure generated by the food coloring is negligible). Furthermore, this system has been successfully implemented as a demonstration in UCONN's Membrane Separations course for senior undergraduates and graduate students. The experiment was used to introduce students to more advanced aspects of RO, generating data from which students could calculate hydraulic permeability, salt rejection, and CP modulus.

3.6 Concluding Remarks

This chapter has described the design and use of a versatile reverse osmosis system that has been implemented in the chemical engineering senior laboratory capstone course at the University of Connecticut. Students learn the fundamental performance variables critical to membrane separations, namely permeability and solute rejection. Furthermore, the concentration polarization aspect of this experiment introduces students to a complex mass transport problem while reinforcing mass transport boundary layer theory.

Once students analyze their data and determine the permeability and rejection of the membranes, they must think critically about possible applications for each membrane they tested, based on each membrane's permeability and salt rejection. Students must consider vital parameters to the RO desalination process, such as feed water salinity, desired permeate water quality and quantity, and operating power requirements and restrictions. While designed as an experiment for the undergraduate laboratory course, this portable system has curriculum-wide applications, such as providing demonstrations to freshman-through-graduate-level classes in addition to demonstrating a chemical engineering process to prospective students.

3.7 Nomenclature

A – Hydraulic permeability constant [gal ft^{-2} day^{-1} psi^{-1}]
C – Solute molecular concentration [mol/L (M)]
D – Molecular diffusivity of solute in water [m^2/s]
d_h – Hydraulic diameter of channel [m]
i – Ionic dissociation constant of solute [mol ions/mol molecules]
J_w – Volumetric water flux [gal ft^{-2} day^{-1} (gfd)]
k – Mass transfer coefficient [m/s, or gfd]
L – Channel length [m]
P – Pressure [psi]
R – Ideal gas constant [1.205 psi L mol^{-1} K^{-1}]
Re – Reynolds number
%*R* – Observed salt rejection [%]
$\%R_{int}$ – Intrinsic salt rejection [%]
Sc – Schmidt number
Sh – Sherwood number
T – Temperature [K]

Subscripts
b – Property of bulk feed solution
m – Property of feed solution at membrane interface
p – Property of bulk permeate solution
eff – Effective conditions at the membrane interface
laminar – Equation for laminar flow
turbulent – Equation for turbulent flow

Greek
μ - Fluid viscosity [kg m^{-1} s^{-1}]
π - Osmotic pressure [psi]
ρ - Fluid density [kg/L]
υ - Fluid crossflow velocity [m/s]
Δ - Difference evaluated between feed and permeate conditions

CHAPTER 4

TEACHING MASS TRANSPORT LIMITATIONS USING FORWARD OSMOSIS

Originally published as:
"Using forward osmosis to teach mass transfer fundamentals to undergraduate chemical engineering students"
by D. Anastasio & J. McCutcheon
in *Desalination* **312** (2013)

4.1 Introduction

The increased need for clean water worldwide has prompted an increased use of nontraditional sources that include wastewater, brackish water, and seawater. Desalination technologies can be implemented to treat these waters, but the high operating and capital costs limit their widespread use to arid regions where few other freshwater sources are available.

The high costs of desalination have spurred efforts to develop desalination alternatives. One such technology is known as forward osmosis (FO), which utilizes an osmotic pressure gradient to drive water flux through a membrane. Water flows naturally from the feed into a highly concentrated draw solution, which is designed such that the draw solute is easier to extract from water than the feed solutes. Therein lies the primary advantage of FO over a conventional membrane desalination technique such as reverse osmosis (RO): water transport is enabled without requiring an applied pressure. The energy requirements are instead directed toward regeneration of the draw solute, where the separation technique can be chosen and optimized based on the solutes available. This unique feature makes FO a cutting-edge separations technology (McGinnis *et al.*, 2007).

As water treatment, desalination, and membrane technology become more commonplace in industrial processes and separations, employers will demand that new engineering students have the knowledge and skills that prepare them to be an engineer in the 21st century. As such, curricula must continually be tuned to incorporate new material, especially in the capstone laboratory course common to many engineering disciplines. In this

study, a crossflow FO test system was constructed for the Chemical Engineering (CHEG) Laboratory curriculum at the University of Connecticut (UConn) as part of a newly implemented membrane separations laboratory module. The first part of the module includes a crossflow reverse osmosis (RO) and nanofiltration (NF) system that embodies a more conventional membrane separations approach of pressure driven filtration (Cath *et al.*, 2006). The second part of this module is the FO component. In this lab, students are asked to analyze membrane water and salt flux behavior in forward osmosis conditions under a wide variety of operating conditions. The first of its kind used to educate undergraduate students on the basics of FO, this experimental system is designed to reinforce mass transfer fundamentals learned in the transport phenomena lecture course common to any CHEG curriculum.

FO serves as an excellent platform for experiential teaching of mass transport fundamentals using the context of novel membrane separations. During the experiment, students gain experience evaluating key FO membrane performance characteristics such as water flux and solute flux. The ratio of these two values, commonly known as the specific reverse solute flux, allows students to understand how effective a membrane is when operating in FO. This experiment is also designed to reinforce basic mass transfer boundary layer theory through an examination of concentration polarization (CP) and how performance variables are impacted by the orientation of the membrane. In FO, CP impacts the solute concentration at the membrane interface, which results in decreased driving force and membrane performance. Students will observe how the degree of CP is impacted by various process parameters, such as cross flow velocity rate and membrane orientation. Ultimately, students must determine which membrane and/or operating conditions are best suited for FO, considering membrane permselectivity and reasonable goals for an FO process. Further discussion can be fostered by having students consider other parameters that are vital to a complete FO desalination process, such as draw solution chemistry and recovery methods, These same methods have been used

only in very recent investigations within the FO community and students participating in this lab are amongst the first undergraduates in the world to learn these skills.

4.2 Theory & Background

Forward osmosis theory is presented to students via a review paper written by Cath, Childress, and Elimelech (2006). The water flux, J_w, is commonly measured in either gallons per square foot of membrane per day (GFD) or liters per square meter of membrane per hour (LMH). The experiment generates data in the form of a mass flow rate of water, which students can convert to a volumetric flow rate using density. Normalizing this flow rate by membrane area results in flux. The generalized flux equation for FO is shown as equation 4.1.

$$J_w = A(\Delta\pi - \Delta P) \qquad (4.1)$$

where A is the hydraulic permeability constant, $\Delta\pi$ is the osmotic pressure difference across the membrane, and ΔP is the applied pressure gradient (which is 0 when feed and draw solutions are at equal hydraulic pressure). The osmotic pressure of a given solution, π, can be calculated using the idealized form of the van't Hoff equation, below:

$$p = iCRT \qquad (4.2)$$

where i is the ionic dissociation constant, C is the molar concentration of solute, R is the gas constant, and T is the temperature. As i, R, and T are constant during each experimental test, it can be said that C has a direct, linear relationship with osmotic pressure p. This is a reasonable assumption for the concentrations of the solutions considered here.

Concentration polarization has long been a topic of discussion and research in reverse osmosis. In FO, permeate gives rise to an additional boundary layer at the draw-solution interface of the selective layer which results in a lower concentration of salt at the membrane interface as shown in Figure 4.1, resulting in a lower net driving force. This phenomenon has been previously examined and is based on the CP modeling work of McCutcheon and

Elimelech (2007). After setting up and solving a simple shell balance around the boundary layer, students can determine that the CP equation for the draw solution in FO is as follows:

$$\frac{C_{m,d} - C_f}{C_{b,d} - C_f} = \exp\left(\frac{-J_w}{k}\right) \qquad (4.3)$$

where $C_{m,d}$ is the draw concentration at the membrane interface, $C_{b,d}$ is the draw concentration in the bulk solution, C_f is the bulk concentration of the feed, and k is the mass transfer coefficient. The appropriate osmotic pressure terms ($p_{m,d}$, $p_{b,d}$, p_f) can replace the concentration terms in equation 4.3 as osmotic pressure is directly proportional to concentration. Equation 4.4 can be used to calculate concentration of solute at the membrane interface, which can be used to determine the CP modulus ($C_{m,d}/C_{b.d}$), a quantity always less than one for FO. Low CP moduli indicate large boundary layers and are caused by low fluid crossflow rates (low k) or high water flux values.

On a fundamental level, the mass transfer coefficient, k, is defined as the ratio of the molecular diffusivity constant D to the thickness of the solute boundary layer d ($k = D/d$). Students will have difficulty using this definition, however. While there are numerous tables and equations for the determination of D, there is no way to measure the thickness of the boundary layer. Therefore, the most practical way to determine k is to evaluate the Sherwood number (Sh = kd_h/D) using correlations provided by Mulder for flow in a channel (Mulder, 1996). Now, equations 4.1, 4.2, and 4.3 can be combined and iterated to estimate the water flux for the known bulk concentrations, shown below:

$$J_w = A(\Delta\pi) = A\left(\pi_{m,d} - \pi_f\right)$$ (4.4) (from Eq. 4.1)

$$\pi_{m,d} - \pi_f = \left(\pi_{b,d}\right)\exp\left(\frac{-J_w}{k}\right) - \pi_f$$ (4.5) (from Eq. 4.2 & 4.3)

$$J_w = A\left[\left(\pi_{b,d}\right)\exp\left(\frac{-J_w}{k}\right) - \pi_f\right]$$ (4.6)

Note that this model assumes that the membranes are run in the pressure retarded osmosis (PRO) mode, where the active layer of the membrane faces the draw solution. Furthermore, the model assumes that feed concentration is sufficiently low and the membrane is highly selective such that internal CP is negligible. This assumption is not always true, but for undergraduate level mass transfer, it provides reasonably accurate results, much as it did for previous studies (McCutcheon & Elimelech, 2007). For further background on CP for RO applications, refer to Sablani et al (2001).

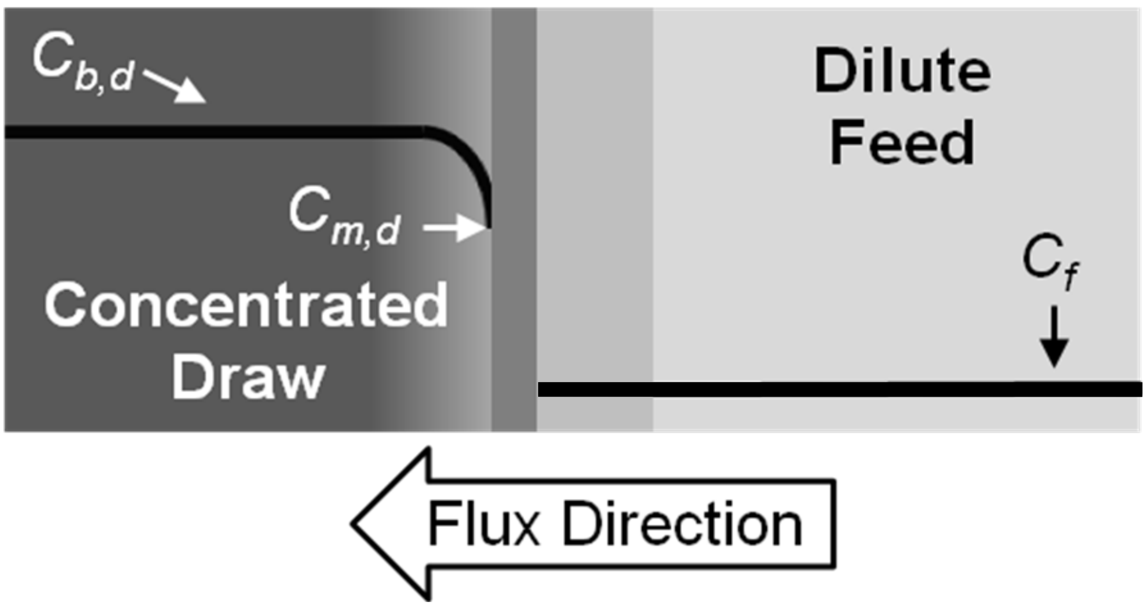

Figure 4.1: Diagram showing concentration polarization CP phenomena for osmotic flow in PRO mode with no transmembrane hydraulic pressure gradient and deionized water feed. The dark gray vertical line is the active layer of the membrane, and the light gray vertical line is the support layer of the membrane. Note that salt concentration (indicated by the black line) of the draw decreases with proximity to the membrane interface, lowering the effective driving force ($p_{m,d}$ - p_f). This diagram assumes no salt crossover from the draw solution.

Finally, the solute flux, commonly referred to as J_s, is calculated similarly to water flux, as shown in equation 4.7 below:

$$J_s = B(\Delta C_{eff}) \qquad (4.7)$$

where B is the solute permeability coefficient and ΔC_{eff} is the effective concentration gradient, which is equal to $C_{m,d}$ - C_f. Note that equation 4.7 accounts for external CP. It is typically desired to calculate A and B values for membranes using a reverse osmosis test; these values

would be considered a more accurate *A* and *B* as concentration polarization (CP) effects are more easily quantifiable in RO. The RO permeability values can be used as a point of comparison to student-generated FO data.

4.3 Experimental Overview

This undergraduate experiment explores how membrane properties (material and orientation) and operating conditions (draw concentration, operating temperature, and flow rate) influence the osmotic flux through a membrane. A system diagram of the cart-mounted FO system is presented as Figure 4.2. A FO membrane coupon that had been stored overnight in deionized (DI) water is sealed within the membrane cell. Feed and draw tanks are filled with DI water. The draw tank is placed on a balance and both solutions are circulated through the system to purge any air out of the lines, which will cause errors in flux measurement. Once the balance has stabilized, concentrated saline stock solution is added to the draw solution, and draw solution mass change is recorded every minute. At regular time intervals, additional saline stock solution is added to the draw to increase the concentration, and the conductivity and temperature of the feed are recorded. From these observations, the water flux and salt flux for each draw solution concentration can be calculated, permitting the estimation of the water and solute permeability constants for the membrane. Furthermore, the draw solution concentration at the membrane surface can be predicted at a given set of experimental parameters (draw concentration, crossflow rate, etc.) using boundary layer film theory (Mulder, 1996, Baker, 2004). This prediction is then compared to the experimental data, and the quality of data and validity of model assumptions are assessed.

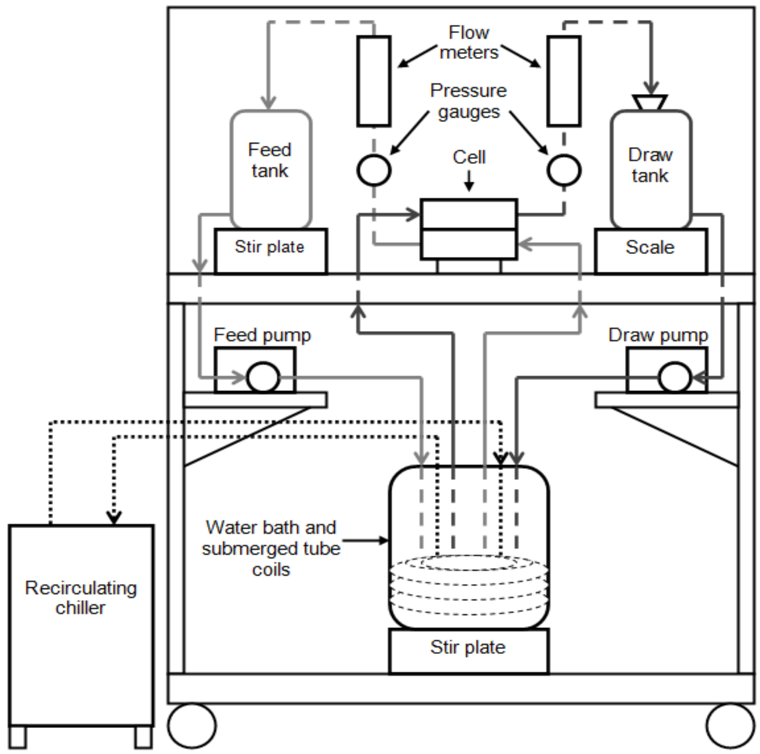

Figure 4.2: Schematic for cart-mounted crossflow forward osmosis system

Individual FO tests require approximately 3.5 hours for a complete examination of one membrane coupon, including set-up, water and salt flux measurements at four draw concentrations, and a system flush. Prior to the experiment, students read an operation manual (Anastasio, 2015). A two-day laboratory schedule provides students with the opportunity to test two different membrane parameters (orientation, material, etc.). Due to the large number of independent variables related to non-membrane process parameters (feed and draw concentrations, feed and draw flow rates, temperature, etc.) the schedule can be expanded to multiple days, or different student groups can be assigned different experimental variables to evaluate. At UCONN, however, the experiment has been coupled with a reverse osmosis experiment for a six-day membrane separations experimental module. The RO experiment utilized in this module tasks students with characterizing membranes for their hydraulic permeability and solute permeability while encouraging them to explore how process conditions impact membrane performance and CP (Anastasio & McCutcheon, 2012). The two systems are

run simultaneously, allowing students to fully characterize a single FO membrane in both orientations with replicate data for error analysis, as well as acquiring permeability and selectivity data (notably the true hydraulic and solute permeability of the FO membrane) from the RO tests. The additional data provided by the RO tests can enhance FO data analysis, but is not required if the experiment is to be performed as a demonstration of boundary layer effects.

4.4 Required Equipment

4.4.1 Membrane

This experiment requires the use of commercially available forward osmosis membranes. Previous investigations have indicated that commercial RO membranes exhibit poor flux performance in FO (McCutcheon *et al.*, 2005, Lee *et al.*, 1981); therefore, commercial RO membranes are not recommended for this experiment as little meaningful result can be garnered. Hydration Technologies Innovations (HTI) produces two types of FO membrane intended for use in freshwater purification with a sugar-electrolyte based draw solution.

For this experiment, the HTI Hydrowell cartridge membrane is used. This membrane is the same used in previous investigations on FO (Martinetti *et al.*, 2009, Achilli *et al.*, 2009, Garcia-Castello *et al.*, 2009, McCutcheon & Elimelech, 2006, Wang *et al.*, 2010). The membrane is an integrated asymmetric cellulose acetate membrane that is supported by a woven mesh. HTI makes another type of membrane used in its X-Pack and Sea Pack products. These can also be used, though they tend to have lower flux and are supported by a nonwoven fabric.

Other companies, such as Oasys Water (Boston, MA), are beginning to make new commercially available FO membranes using materials other than cellulose acetate. HTI has also developed of a thin film composite membrane (Prankratz, 2012). These and other membranes are also worth considering for this experiment, though were unavailable at the time

of this study. Note that membranes made of materials other than cellulose acetate may require additional preparation and storage steps.

4.4.2 Cell Design

The custom-made FO cell is composed of two identical halves fabricated from black delrin with stainless steel plates acting as additional support. Each half has a crossflow channel with dimensions 3” long by 1” wide by 1/8” deep that is fed via threaded ports bored into the sides of the cell. Surrounding the channel on the bottom half are two concentric o-rings, one approximately 1 cm larger in radius than the other, that are seated in grooves bored into the delrin; the top half only contains the smaller o-ring. The small o-rings seal against the membrane, while the outer o-ring creates a watertight seal around the membrane. The two halves are placed on threaded stainless steel rods that are attached to a stainless steel base plate, which can easily be mounted to a surface. The cell halves are sealed and supported using washers and nuts. Figure 4.3 shows photographs of the cell interior and exterior.

a)

b)

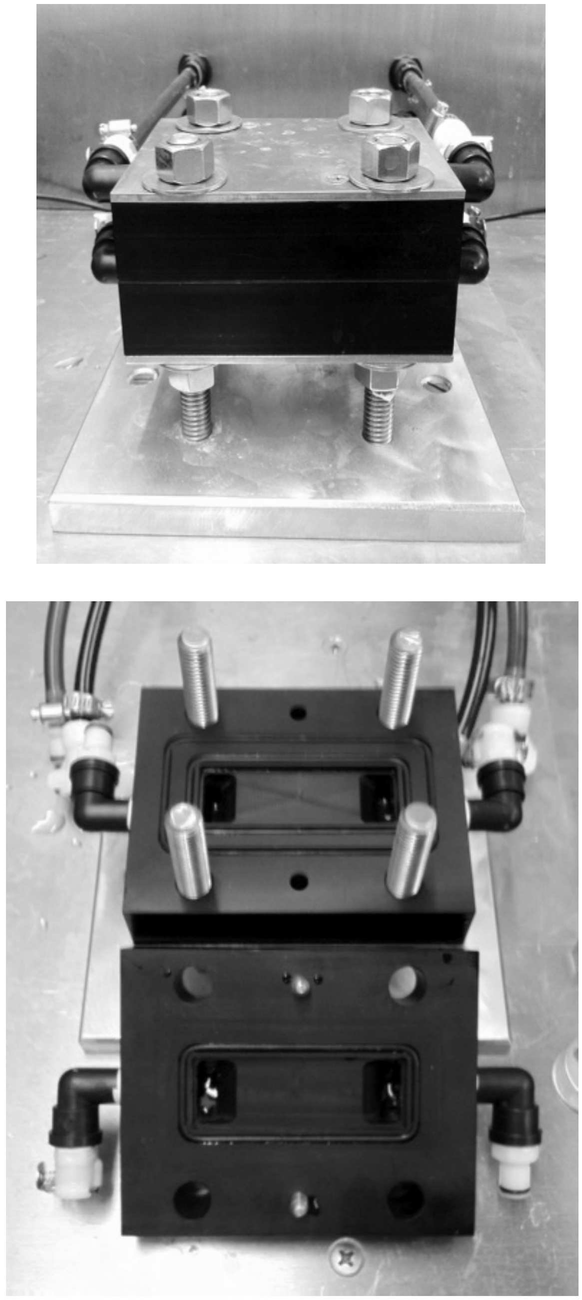

Figure 4.3: Photographs of forward osmosis test cell; (a) exterior, (b) interior

Larger cells can be designed to accommodate larger membrane coupons, though we have found this size to be appropriate given the flux measurement method and the desire to preserve membrane. This will give the user a greater ability to measure low fluxes and provide a greater sensitivity to flux changes as the system changes. The current cell size was chosen

for several reasons: 1) it matches the dimensions of the RO cells used in the previously-mentioned RO experiment (Anastasio & McCutcheon, 2012); 2) uses smaller coupons to conserve membrane; and 3) fluxes through commercial FO membranes can be accurately measured using this membrane area. If the flux is too low to be accurately measured through this amount of membrane area, then the membrane performance is likely too poor to be considered for this experiment.

4.4.3 Key System Components

To support the system, a cart (36" tall x 30" wide x 20" deep) was fabricated with an angle-iron frame, painted to resist corrosion, and aluminum plates. Four locking, swiveling wheels were added for increased mobility. A 24" tall aluminum backsplash was added to support pressure gauges and flow meters as well as to provide support for stream return lines. Two 10"-wide shelves were added under the top shelf to hold the draw and feed pumps. Figure 4.4 shows a photograph of the completed cart. Note that all lines connected to vibrating equipment (pumps, chiller, etc.) pass through a rigid surface, such as the countertop or backsplash to reduce the vibration around the scale during the gravimetric data acquisition. Without this design consideration, system stabilization will become too long to permit a thorough membrane examination within a laboratory period. Additional vibrational prevention measures, such as adding a foam pad beneath the scale, adding Velcro strips to the scale and draw container, or covering the scale with a wind guard, may also help achieve faster stabilization.

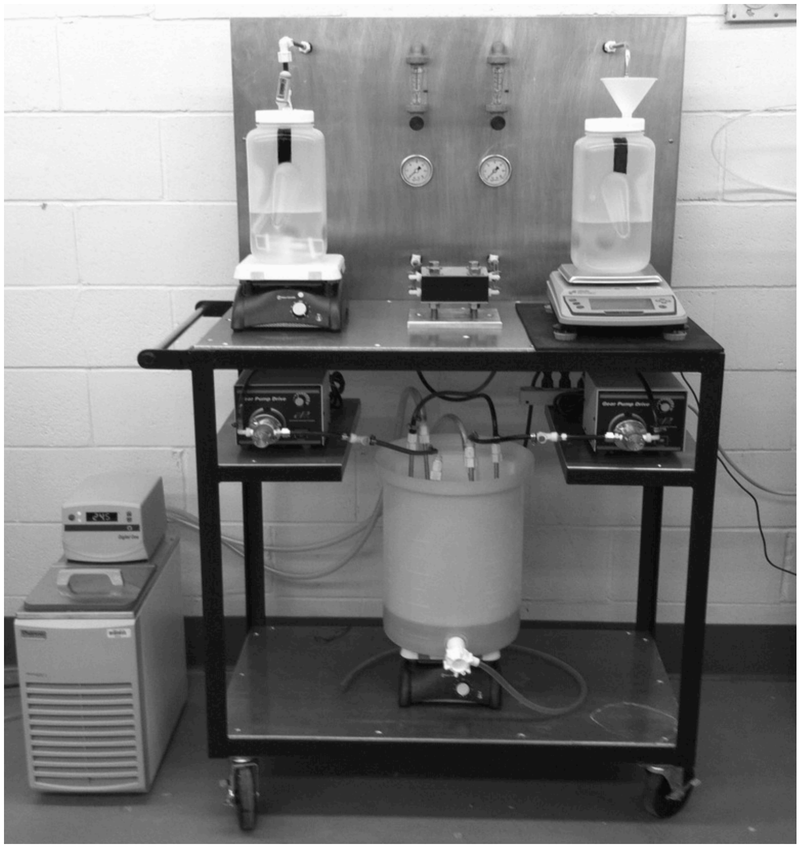

Figure 4.4: Photograph of the completed FO system cart

Two 5-L polyethylene bottles from McMaster-Carr (Princeton, NJ) were selected to serve as the feed and draw tanks. Each tank is connected through the tabletop using flexible color-coded PVC tubing to distinguish feed and draw lines. These lines connect to Micropump variable-flow gear console drive gear pump (fitted with A-Mount cavity style pump heads) from Cole-Parmer (Vernon Hills, IL). The draw solution reservoir sits on a PI-4002 Denver Instruments top-loading balance with 4000.00 g capacity (Fisher Scientific), which comes packaged with the appropriate data-logging software, and the feed tank is placed on a magnetic stir plate (Fisher). To regulate the temperature of the streams, a 25' coil of welded 316 stainless steel tubing was cut into thirds, which were fashioned into concentric heat exchange coils. The outermost and innermost coils are connected to the feed and draw lines, respectively. The center coil is connected to a Neslab RTE7 recirculating chiller (Fisher). All three coils are submerged in a 5-gal polypropylene tank containing DI water that is agitated with a magnetic stir

plate (Fisher). To conserve space, a shell and tube or concentric tube heat exchanger may be substituted. Note that the chiller must not be in contact with the cart during operation to minimize vibrations. A pair of quick-disconnect fittings (without check valves) were placed in the tubing of the feed and draw lines between the pumps and the heat exchanger coils to allow air purging of the lines between tests. After passing through the heat exchanger, the streams are fed through the backsplash and into the cell countercurrent. Each line is connected to the cell with quick-disconnect fittings to facilitate cell disassembly. Outlet streams from the cell are directed through the backsplash to two glycerin-filled, panel-mountable pressure gauges (0-30 psi, McMaster), followed by two panel-mountable flow meters with built-in needle valves (0-1 gpm, McMaster). The feed return line is connected directly to the feed tank via quick-disconnect fitting. Draw returns to the draw tank via a stainless steel pipe that drains into a funnel in the draw tank lid, as shown in Figure 4.5. A tube extends from the funnel stem into the draw solution to minimize vibrations from splashing. For best results, the tank should be centered on the scale and the return should drain into the center of the funnel. It is crucial that all metal components in the system be 316 stainless steel to minimize the corrosion high salt concentrations promote. All tubing, pipe, and pipe fittings were purchased from McMaster, unless otherwise specified. A summary of the approximate cost of each major system component is provided in Table 4.1.

Figure 4.5: Photograph of draw solution return line. The return is not directly connected to the draw tank in order to minimize vibrations on the scale. This is a viable approach for non-volatile draw solutes.

Table 4.1: Approximate Cost of System Components

Component	**Supplier**	**Approx. Cost**
Recirculating chiller	Fisher Scientific	$2,000
Gear pump drives & heads	Cole-Parmer	$2,000
Denver Instruments Scale	Fisher Scientific	$2,000
Test cell	n/a	$500
Custom cart	n/a	$500
Tanks	McMaster	$100
Meters & gauges	McMaster	$250
Tubing, piping, & fittings	McMaster	$600
Stirrers & Floating Stir Bar	Fisher Scientific	$300
Conductivity probe	Fisher Scientific	$600
Total		**$8,850**

4.4.4 Measurement Devices

To utilize the automatic data-logging feature of the scale, a computer capable of running Microsoft Excel with a USB port is needed. It is recommended that the screen saver and

automatic sleep mode be disabled so data collection is not interrupted. An Oakton conductivity probe with built-in temperature probe (Fisher) was used to monitor the condition of the feed solution. Holes should be drilled in the feed tank lid to accommodate these probes. The conductivity probe should be calibrated to the selected draw solute prior to the test, which can easily be accomplished by measuring the conductivity of a serial dilution of a 2000 ppm stock solution.

4.5 Experimental Procedure

At least 24 hours prior to the experiment, membrane sheets must be cut into small coupons for student use. The coupons should be stored in refrigerated DI water to prevent membrane damage and biological growth. It is advised that the hydraulic and solute permeability of these membranes be determined, either through an RO test or by contacting the manufacturer, as this information can be used to enhance student analysis and understanding. Again, students could perform such an RO test themselves as part of the experiment if time permits [9]. Additionally, two liters of 5 M sodium chloride stock solution should be prepared. While other salts can be considered, the high solubility limit of sodium chloride ensures this stock will last for four complete membrane tests. This salt is also inexpensive when purchased in large quantity. Safety goggles should be worn as part of good laboratory practice.

At the start of each test, a membrane was loaded into the cell. Gloves were worn to minimize damage to the membrane, and the membrane was cut with scissors so it would fit between the small and large o-rings in the cell. Great care was then taken to place the membrane's active layer against the draw side of the cell for initial tests. This orientation, known as PRO mode, allows for simplified mass transfer modeling appropriate for undergraduate students. Students may elect to run a test in FO mode, where the active layer faces the feed solution, but the transport phenomena are complicated by internal concentration polarization caused by the interaction of the draw solution with the support layer. The membranes may curl

slightly when loaded, so a spatula or DI water were used to gently flatten the membrane as the top was being placed on the cell to prevent folding.

As the feed and draw tanks were filled with 2 L of DI water each, the recirculating chiller was set to approximately 25 °C, adjusting the setting depending on ambient air temperature to ensure that the feed was 25 °C during the run. Both the feed and draw pumps were turned on, and once no bubbles were observed in the lines, flows were set to 1 LPM using the control knobs on the pumps. Feed and draw pressure can range from 0 to 5 psi, but both streams were set to the same pressure. The data acquisition software was started to record the mass of the draw tank. During this equilibration step, the scale registered losses in mass as air is purged from the system. Once the minute-to-minute change in draw mass was ±0.05 g, the system was considered stable; this process typically took under 10 minutes if the system was well-designed. If the scale does not stabilize in this time period, center the tank on the scale and minimize all sources of air currents, using cardboard or plastic to construct a wind shield if necessary. Once the system was stable, saline stock solution was added to the draw, which increases the stream concentration to a known molarity, and the conductivity and temperature of the feed were measured. The data acquisition software collected 1-2 points of data per minute for 30 minutes. After 30 minutes, the draw solution concentration was increased, feed conductivity and temperature were measured, and the process was repeated. Recommended draw solution concentrations are 0.05 M, 0.1 M, 0.5 M, and 1 M. At the highest concentration, students usually alter an independent variable, such as temperature or flow rate, and continue to take data as time permits. Table 4.2 summarizes typical testing conditions utilized by students in the unit operations laboratory.

Table 4.2: Typical Operating Conditions for Student Experiments

Variable	Typical Draw-Side Value	Typical Feed-Side Value
Temperature (°C)	25	25
Gauge pressure (psi)	0	0
NaCl concentration (M)	0, 0.05, 0.1, 0.5, 1.0	0
Initial DI water volume (L)	2	2
Hydraulic flow rate (L/min)	1-2	1-2
Frequency of mass measurement (recordings/min)	1	n/a

Once a membrane test was complete, the tanks were emptied and refilled with DI water. The outlet lines were extended with flexible tubing placed in a bucket or drained directly into a sink. The water was pumped through the system into the sink or bucket, and the tanks were refilled with DI water as needed. Flushing continued until the conductivity of each outlet stream was below 10 microsiemens (μS). If DI water is in short supply, tap water may be used for an initial flush and about 1 gal of DI water can be used per tank as a polishing wash. Filtered compressed air was then used to purge the lines of residual water by connecting the air line to one of the air purge ports. Low-pressure air was applied until the lines had been evacuated. Great care should be taken during this step to avoid spiking the pressure gauges. Once both lines are purged, the membrane was removed from the cell, checked for defects, and discarded.

The versatility of this system permits many other tests using different independent variables. The independent variables mentioned here are membrane type, membrane orientation, draw concentration, and temperature. Additionally, feed and draw flow rate, draw solute type, and feed solution concentration can also be varied.

4.6 Typical Results and Discussion

The primary results students will present when running this experiment are water flux (J_w) and salt flux (J_s). To facilitate experimental analysis, students frequently assume the feed and draw solutions are dilute; therefore, the solution is ideal, the properties r and μ can be evaluated for pure water at the appropriate temperature, and solute diffusivity D can be approximated using the Nernst-Haskell equation. While this assumption is always appropriate

for the feed, it becomes invalid for draw solution concentrations greater than 0.1 M. Students find the assumption of ideal draw solution remains a tolerable approximation for the purposes of this experiment. If other draw solutes are used, students may choose to measure density and viscosity for more accurate mass transfer modeling.

Flux is plotted against the observed osmotic pressure difference, as shown in Figure 6, which summarizes the results of several FO tests for the HTI cartridge membrane in PRO mode with standard deviation error bars. Note that the FO fluxes are lower than pure water flux in RO under equivalent pressure driving force (the upper dashed line in Figure 4.6). The lower flux is a result of CP, which reduces the osmotic driving force.

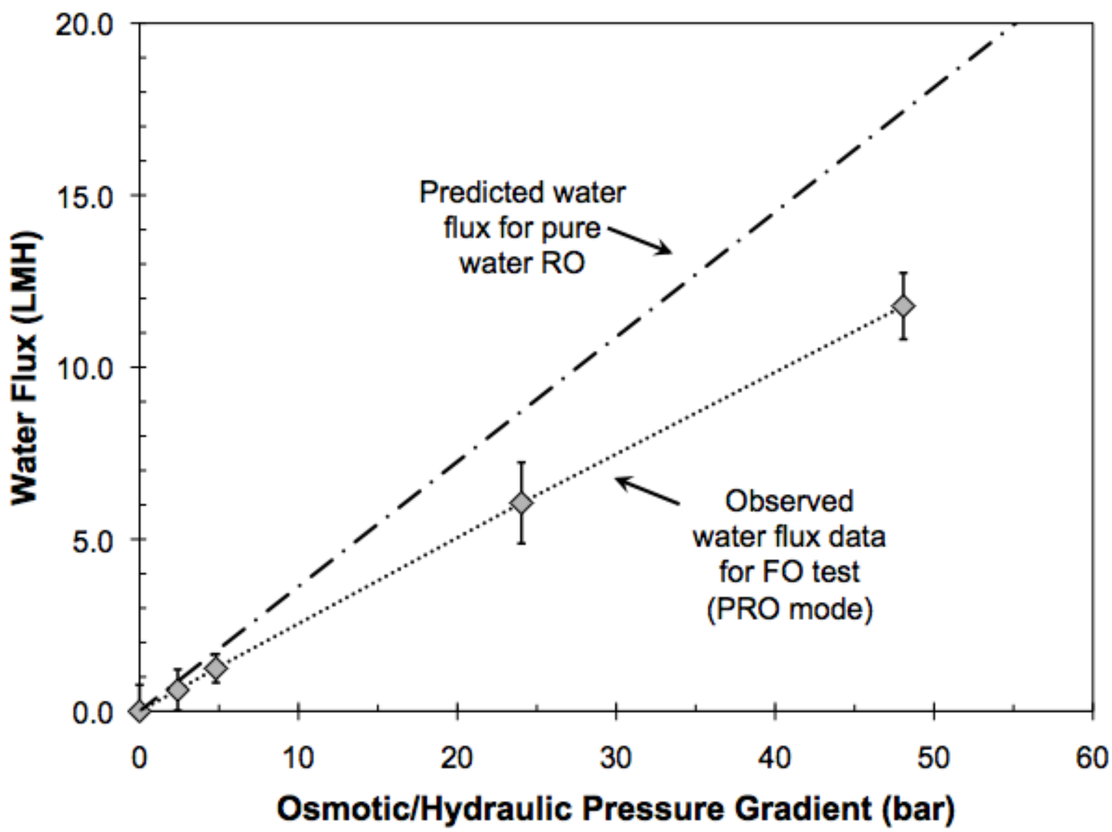

Figure 4.6: Water flux as a function of driving force (osmotic pressure for FO and applied pressure for RO) for HTI cartridge membrane (25 °C, feed and draw flow rate at 1 L/min). The lower dashed line is a linear trend line for the FO data. Note that 1 gfd is approximately 1.7 $L/m^2 h$. The data points are an average of three student tests, with the error bars representing standard deviation.

A parity plot of predicted water flux based on film theory and water flux measured by a group of students is presented as Figure 4.7. This data was collected during pilot testing of the system in the laboratory course. The students accounted for external CP on the draw side of the membrane when analyzing their data. By performing this calculation using equation 6, the students observed a decrease in external CP modulus with increased flux, indicating a worsening of concentration polarization effects. The plot shows that the model is very accurate at predicting fluxes at low draw solution concentrations. As higher concentrations are reached, the model tends to over-predict flux, likely caused by the model's neglecting of internal CP effects caused by salt diffusion across the membrane or the assumption of ideal draw solution. Membranes run in FO mode will exhibit lower flux due to significant internal CP acting directly on the draw solution. For further reading on internal CP and impact of membrane orientation, consult McCutcheon *et al.* (2006), McCutcheon & Elimelech (2008), and Gray *et al.* (2006). During the lab, students are encouraged to search the peer-reviewed literature to learn about these more advanced concepts.

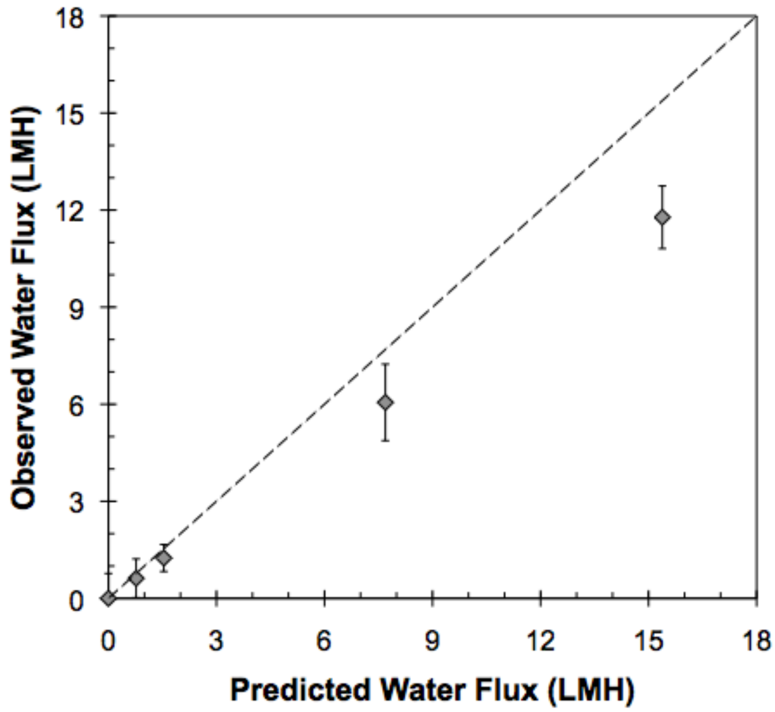

Figure 4.7: Parity plot of experimentally observed experimental water flux versus water flux predicted using boundary layer film theory model for draw concentrations of 0, 0.05, 0.1, 0.5, and 1.0 M sodium chloride in PRO mode. Error bars indicate standard deviation.

Salt flux is calculated by normalizing mass flow rate of salt into the feed tank by membrane area. The summary of salt flux data at effective concentrations (accounting for CP on the draw side) for several tests made in the PRO mode using the HTI cartridge membrane is presented as Figure 4.8. Students will see that for high-concentration draw solutions, there is a high salt crossover into the feed solution in addition to a high water flux. In order to help students understand how to optimize the FO process, they must calculate the specific reverse salt flux (Hancock & Cath, 2009, Phillip *et al.*, 2010), which is the ratio of the solute flux to the water flux and typically has units of g/L. In other words, specific salt flux denotes the mass of solute that permeates into the feed solution per volume of water that passes into the draw. Ideally, this value should be as small as possible, denoting that salt flux is much smaller than water flux. For the HTI cartridge membranes, students have observed specific reverse salt fluxes between 0.85 and 1.3 g/L during their experiments.

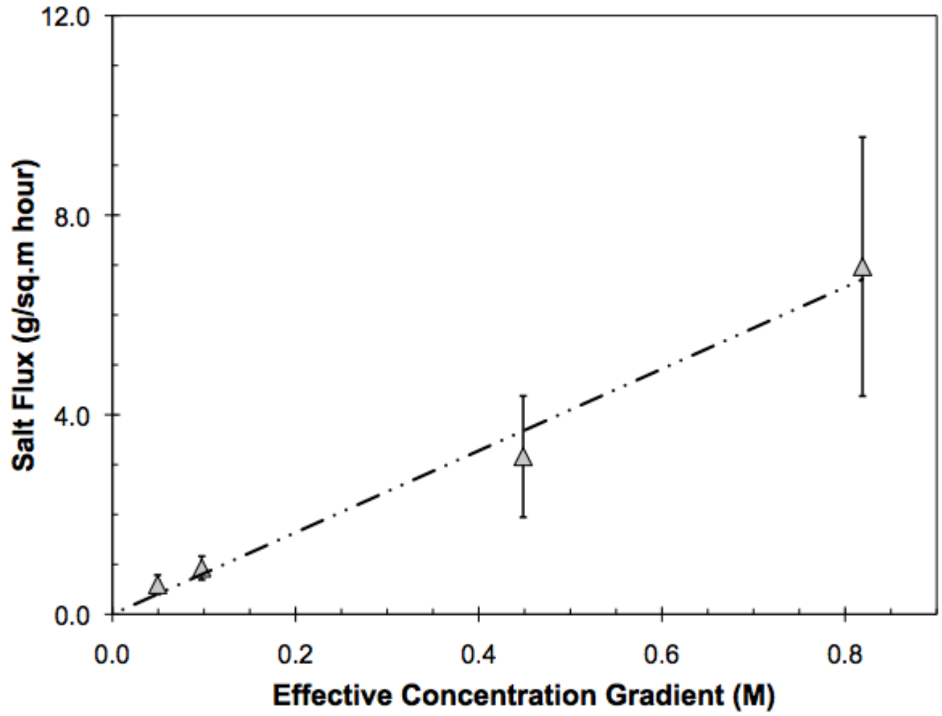

Figure 4.8: Observed salt flux for HTI cartridge membrane in PRO mode as a function of effective concentration gradient. Error bars indicate standard deviation.

There are a number of other independent variables that can be changed to demonstrate other fundamental mass transfer concepts. Feed and draw flow rates can be altered to see the impact of crossflow velocity, and by extension Reynolds number, on water flux through the membrane. If flow velocity has been altered, it is expected that more turbulent flows will diminish the thickness of the boundary layer, decreasing the severity of CP and increasing water flux. This study would help students understand the interplay between the variables that contribute to CP effects. Students could effectively mitigate the CP effects at high draw concentrations by increasing fluid velocity to decrease the thickness of the boundary layer. Varying temperature can help students learn how water viscosity impacts water and salt permeability coefficient. Different draw solutes, such as sugars, multivalent salts, and blended solutes, would provide students an opportunity to learn more about colligative properties and the properties of an ideal solution. For more advanced students, both PRO and FO mode can be tested and students challenged with explaining why the fluxes for the same membrane in two orientations are

different. The system is extremely versatile, and if students can alter these variables independent of one another, they will be able to hypothesize if, how, and why water and salt flux will change and justify their reasoning with mass transfer theory. When coupled with an RO experiment, students will gain an even better understanding of membrane processes while gaining a comprehensive understanding of concentration polarization phenomena.

All data presented in this manuscript has been generated by UCONN chemical engineering undergraduate students using the experimental apparatus and the HTI cartridge membrane oriented in PRO mode. The data was collected over the course of five separate runs of the system. Student feedback regarding this experiment has been positive. At the end of the Fall 2011 semester, students were asked to evaluate how interested they were in the topic, how engaged they felt by the experiment as it was performed, and the students' own perception of how much they learned from all experiments they performed based on a scale of 1 to 5, where 5 was the highest mark. The results of this survey are shown in Figure 4.9. Although error bars were large, student opinion of the osmotic separations module (which contained both a reverse and forward osmosis component) appeared to be higher than the average student opinion of all other experiments in general. Students become comfortable with the material if given an overview paper on the technology, such as the FO review prepared by Cath *et al.* (2006) or the PRO review prepared by Achilli and Childress (2010). Upon completing one membrane test, the students are able to test additional membranes without further assistance. Many students note a large amount of down time during the experiment, as data acquisition takes 30 minutes per draw solution concentration (less time is also acceptable), so they were encouraged to review literature pertaining to the experiment during this time. Early tests were hampered by a failure of the data acquisition software mid-test; however, disabling sleep mode and screensaver on the logging computer solved this problem. In their laboratory reports, students were able to determine water and solute fluxes accurately. Students were challenged by the flux modeling component of the experiment, but many said this component helped them understand factors

that contribute to CP. In Spring 2011, students were given the opportunity to spend four laboratory periods using this system in conjunction with a crossflow RO system (Anastasio & McCutcheon, 2012) to characterize various NF, RO, and FO membranes utilizing an array of independent variables, such as membrane orientation, solute type and concentration, flow rate, system backpressure, and temperature. This exercise allowed students to freely alter these multiple variables to grant them a complete understanding of what impacts permeability, selectivity, and CP using both established and emerging water desalination approaches.

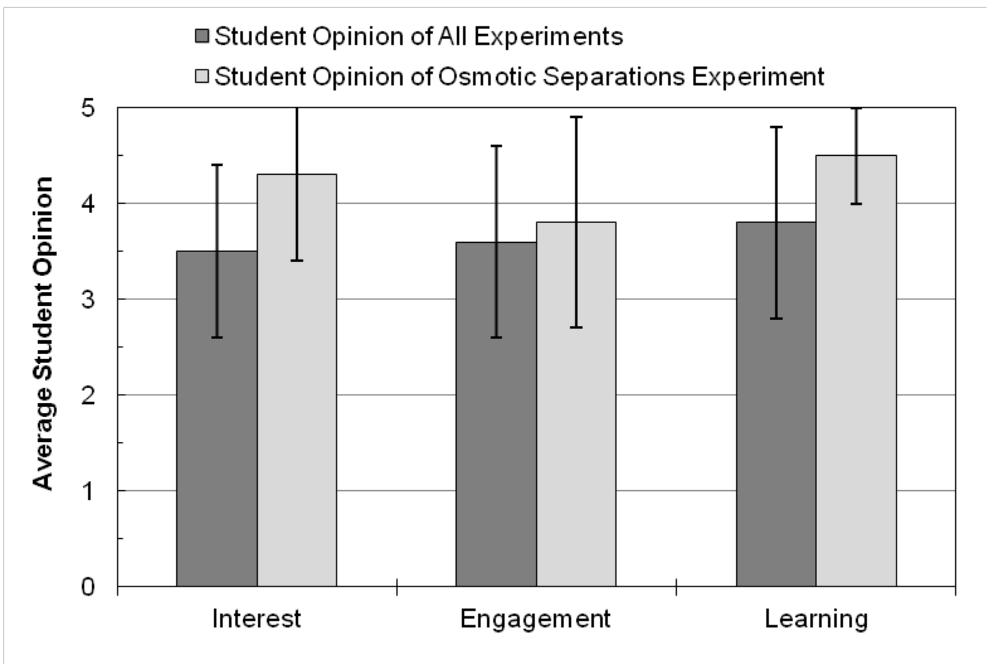

Figure 9: Student opinion of the reverse and forward osmosis experiments at UCONN compared to the average opinion of other experiments in the curriculum. Ratings were given on a scale of one to five, with 5 being the highest option. All opinion scores are based on student self-perception of interest, engagement, and learning. Error bars indicate standard deviation of opinion scores.

4.7 Concluding Remarks

This chapter describes the design and implementation of a forward osmosis membrane testing system for a capstone-level chemical engineering laboratory course. The system is novel in that it is the first FO system designed specifically to be robust and easy-to-use for educational purposes. FO offers a unique learning opportunity for students in that they can explore a separations process that does not rely on temperature or applied pressure as a

driving force. Students will learn to characterize membrane permeability and selectivity will observe how these properties change with membrane characteristics (structure, material, and orientation), hydrodynamic conditions, draw solute concentration and/or type and temperature. The large number of variables allow for many potential laboratory scenarios. Mass transfer boundary layer theory is reinforced by this experiment through a flux modeling component of the analysis. While the system functions very well as a stand-alone experiment, coupling it with a reverse osmosis experiment gives students a complete exposure to established and emerging membrane desalination technologies, highlighting similarities, differences, benefits, and drawbacks of each.

4.8 Nomenclature

A – Hydraulic permeability constant [L m^{-2} h^{-1} bar^{-1}]
B – solute permeability constant [g m^{-2} h^{-1} M^{-1}]
C – Solute concentration [mol/L (M)]
D – Molecular diffusivity of solute in water [m^2/s]
i – Ionic dissociation constant of solute [mol ions/mol molecules]
J_s – Solute flux [g m^{-2} h^{-1}]
J_w – Volumetric water flux [L m^{-2} h^{-1} (LMH)]
k – Mass transfer coefficient [m/s, or LMH]
P – Pressure [bar]
R – Ideal gas constant [0.08314 bar L mol^{-1} K^{-1}]
Sh – Sherwood number
T – Temperature [K]

Subscripts
b - Property of bulk solution
d – Property of draw solution
f – Property of bulk feed solution
m – Property of solution at membrane interface

Greek
δ - Boundary layer thickness [m]
μ - Fluid viscosity [kg m^{-1} s^{-1}]
π - Osmotic pressure [bar]
ρ - Fluid density [kg/L]
Δ - Difference evaluated between feed and draw interfaces

CHAPTER 5

ADAPTING PRESSURE RETARDED OSMOSIS TO THE CHEMICAL ENGINEERING LABORATORY TO TEACH TRANSPORT PHENOMENA AND THERMODYNAMICS

5.1 Introduction

The previous chapters have discussed experiments related to teaching undergraduate chemical engineers mass transport and fluid mechanics principles through the context of reverse osmosis (RO) and forward osmosis (FO). In the case of RO, water is driven from a concentrated solution through the membrane by hydraulic pressure in excess of the osmotic pressure gradient between dilute and concentrated solutions. In FO, no hydraulic pressure is applied, and water flows by osmosis into the concentrated solution. However, a third regime exists, illustrated in Figure 5.1, where a pressure is applied to the concentrated solution that is less than the osmotic pressure gradient. Water will flow into the concentrated draw solution similar to FO, but the net flux will be reduced in comparison. This regime, called pressure retarded osmosis (PRO), may seem undesirable as a desalination method, where high water fluxes are desirable. However, PRO is not a desalination technique; rather, the increasing volume of the draw solution at constant pressure can be harnessed by a hydroturbine to generate power (Achilli *et al.*, 2009, Achilli & Childress, 2010). PRO provides a link between topics related to mass transport and topics related to thermodynamics.

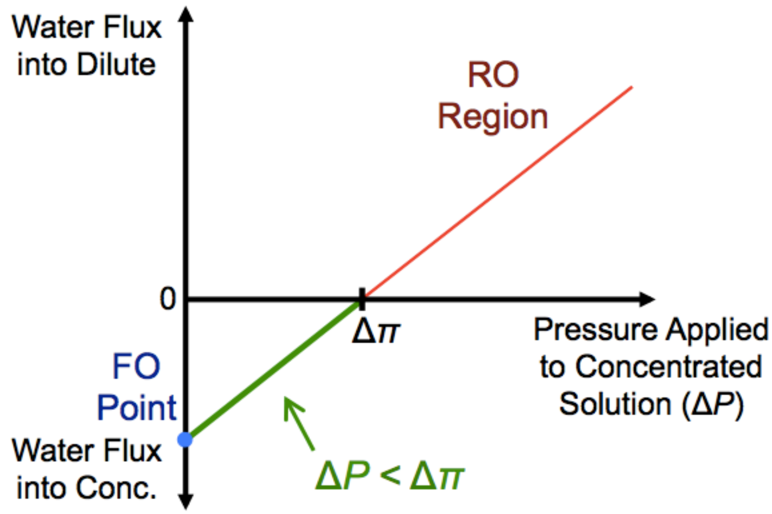

Figure 5.1: Illustration of the three major membrane processes, where positive water flux denotes flux into the dilute solution and negative water flux denotes flux into the concentrated solution (adapted from Cath *et al.*, 2006).

5.1.1 Open-Loop Pressure Retarded Osmosis

PRO has been implemented industrially in an attempt to harness the energy stored in the gradient between river water and seawater. This type of process that relies on working fluids drawn from and discharged to the environment, shown in Figure 5.2, is known as open-loop PRO. Water is drawn across the membrane from the freshwater feed into the pressurized seawater draw. The draw solution is then used to turn a hydroturbine, generating power. Some of the draw solution is diverted through a pressure exchanger to decrease the amount of power required to pressurize the inlet draw stream, which is commonplace method to reduce power draw in industrial RO plants (Migliorini & Luzzo, 2004). Filters are also in place before the membrane unit on both the feed and draw sides to prevent membrane fouling.

A PRO plant using this open-loop configuration was opened by Statkraft in Tofte, Norway, and operated from 2009 to 2014 (Helfer *et al.*, 2014). At its peak, the plant was producing 4 kW of power (Patel, 2014). This low power output was due to the relatively low power density, or power capable of being generated per one square meter of membrane, which was typically below Statkraft's target of 5 W/m^2 for commercial viability (Moskwa, 2009). This low power density could be attributed to the relatively low osmotic pressure gradient between

seawater and fresh water (approximately 27 bar), the high viscosity of cold seawater enhancing concentration polarization, and the relatively low permeability of commercially available forward osmosis membranes (Woode, 2014). However, as shown in the previous chapter, high power density is possible using less permeable membranes if draw solution concentration and temperature can be increased (Anastasio *et al.*, 2015, Straub *et al.*, 2014).

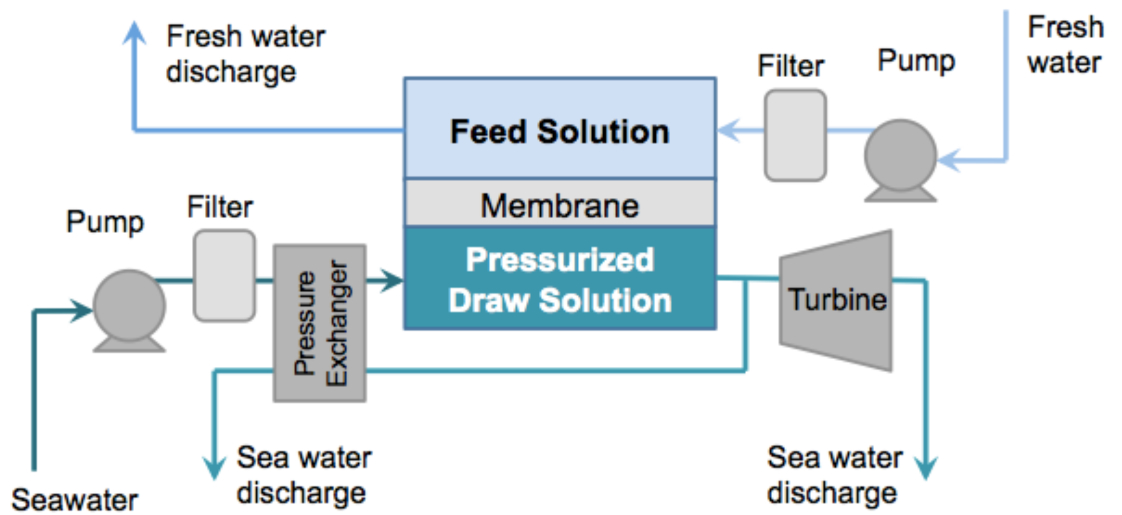

Figure 5.2: A process diagram of an open-loop PRO process. Dark blue lines denote concentrated seawater, and light blue lines denote fresh water.

5.1.2 Closed-Loop Pressure Retarded Osmosis (Osmotic Heat Engine)

To allow for the finer control of draw concentration and temperature while eliminating the need to discharge draw and feed solutions back to the environment, PRO can be run in closed-loop, shown in Figure 5.3. This configuration is known as the osmotic heat engine (OHE) (McGinnis & Elimelech, 2007, McGinnis & Mandell, 2011). In the OHE, the PRO step is run normally, with the pressurized draw solution drawing water across the membrane from a dilute feed solution. The draw solution is again used to turn a hydroturbine while some of the draw is diverted to a pressure exchanger. However, the draw and feed solutions cannot be passed continuously through the membrane element alone in closed-loop. Over time, the draw solution will become dilute and the feed solution will become more concentrated, reducing the net

osmotic driving force for PRO. Thus, a draw solute recovery unit is required. The draw solute recovery unit is designed to use energy to restore both working solutions to their initial concentrations before feeding them back to the membrane. Thus, as long as energy is provided to this unit, the turbine can generate electricity indefinitely. The power of the osmotic heat engine lies in its highly adaptable nature. Any recoverable draw solute may be used, and ideal candidates for draw solutes are ones that require low amounts of energy or low-quality thermal energy to fully extract from solution (McGinnis & Elimelech, 2007, Achilli & Childress, 2010). Therefore, the OHE can effectively convert these sources of low quality thermal energy into useable electricity (McGinnis *et al.*, 2007, McGinnis & Elimelech, 2007). The OHE can additionally enable a form of osmotic grid storage for intermittent energy sources, where the feed and draw solutions are used in a PRO process in times of high energy demand and recovered during periods of high energy supply (McGinnis & Mandell, 2011).

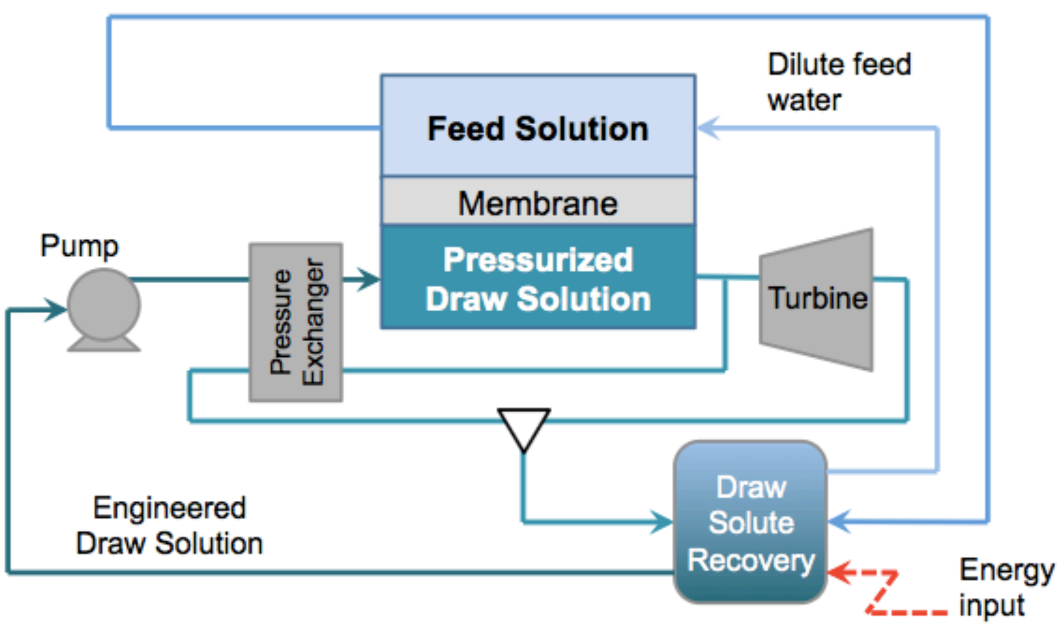

Figure 5.3: General apparatus diagram for an osmotic heat engine, where the exact draw solute recovery method will vary depending on the selected draw solute.

The only other process that can convert low quality or waste heat to electricity is the organic Rankine cycle, where waste heat is used to vaporize a working fluid, such as water,

alcohol, ammonia, or benzene. The vapor powers a turbine and is later condensed for future evaporation (Hung *et* al, 1996, Liu *et al.*, 2002). The simulations of the organic Rankine cycle predict that the efficiency of the cycle (the amount of energy generated by the turbine divided by the amount of energy consumed during the process) tends to range between 5-10%, depending on the operating fluid (Hettiarachchi *et al.*, 2006). Early simulations of the OHE predicted a similar process efficiency of 5-10% (~16% of maximum Carnot efficiency) (McGinnis *et al.*, 2007); however, this efficiency can be increased through the use of newer, more permeable membranes capable of greater power density. To this point, the OHE has only been modeled theoretically, and an experimental apparatus would assist in refining these models. Key factors that potentially limit power density and efficiency, such as the flux through a real spiral-wound membrane module and monitoring of energy consumed by pumps, could be quantified and considered.

A pilot-scale OHE is currently being constructed at the University of Connecticut (UCONN), which will be the first pilot-scale demonstration of the OHE, allowing for process optimization based on physical data rather than predictive modeling. However, once the system has been tested and refined, it could serve a dual purpose as a research and teaching platform, allowing students to learn about multiple unit operations and core chemical engineering concepts in the same experiment. While a PRO experiment has not yet been built or tested with students at UCONN, the purpose of this chapter is to serve as a guide to how to adapt PRO and the OHE to the undergraduate chemical engineering laboratory. An overview of theory, design and safety considerations, and student learning outcomes will be provided.

5.2 Pressure Retarded Osmosis Theory

As is true with FO water flux, PRO water flux through the membrane is driven by an osmotic pressure gradient between the dilute feed solution and concentrated draw solution (Cath *et al.*, 2006, Achilli & Childress, 2010, Helfer *et al.*, 2014). However, in PRO, the draw solution is pressurized, which reduces the net driving force, as shown in equation 5.1:

$$-J_w = A(\Delta\pi - \Delta P) \quad (5.1)$$

Note that in this equation, where a negative flux denotes water transport into the draw solution, $\Delta\pi$ is assumed to be the effective osmotic pressure driving force and that concentration polarization has been taken into account. The volumetric water flux, J_w, increases the volume of the draw solution increases at constant pressure, generating work. The amount of work created in a PRO process is given as:

$$W = P\Delta V = \Delta P|J_w| \quad (5.2)$$

Combining equations 5.1 and 5.2 allow for the creation of a quadratic relationship between power density, W, and applied hydraulic pressure, ΔP, for constant effective osmotic pressure gradient, $\Delta\pi_{eff}$, shown as equation 5.3:

$$W = A(\Delta\pi\Delta P - \Delta P^2) \quad (5.3)$$

By equation 6.3, and as shown in figure 6.4, power density will reach a minimum of 0 both when $\Delta P = 0$, as no pressure is applied, and when $\Delta P = \Delta\pi$, as no water flux occurs at this point. The point at which the water flux transitions from negative to positive, which occurs when $\Delta P = \Delta\pi$, is known as the flux reversal point or the flux inversion point (Achilli & Childress, 2010).

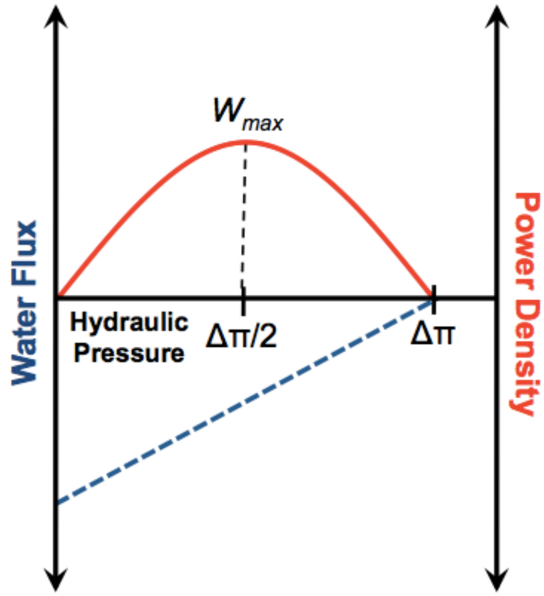

Figure 5.4: Expected trends for water flux and power density for a PRO process as a function of hydraulic pressure, with an anticipated peak power density at $\Delta P = \Delta\pi/2$. Water flux typically has units of L/m^2 hr, and power density typically has units of W/m^2.

By taking the derivative of equation 6.3 to determine its maximum, maximum power density occurs when $\Delta P = \Delta\pi/2$. If this condition is combined with equation 5.3, an expression for maximum possible power density for a given membrane and draw solution can be expressed:

$$W_{max} = A(\Delta\pi^2/4) \qquad (5.4)$$

Therefore, by equation 5.4, it can be shown that the peak power density, W_{max}, of any given membrane used in PRO is a function of *A*, the membrane's hydraulic permeance, and $\Delta\pi$, the effective osmotic pressure gradient. Therefore, membrane and draw solute selection are both critical parameters. Greater concentrations of draw solute will increase the osmotic pressure of the draw, increasing the maximum power density. Furthermore, increasing the system temperature will increase both the osmotic pressure of the draw and the membrane permeance (Mulder, 1996), resulting in greater peak power density. While concentration and temperature cannot be controlled in open-loop configurations due to the use of naturally-occurring feed and

draw solutions, a closed-loop configuration such as the OHE allows for control of these conditions to maximize power density.

5.2.1 Connections to Process Thermodynamics

While the above calculations can be performed by students based solely on PRO tests, an experiment using a complete OHE can teach students about key process thermodynamics concepts such as efficiency. For instance, students may calculate the efficiency of the turbine directly. Students will be able to calculate the power density of the membrane element using the above equations. Students will also be able to measure directly the power being generated by the turbine. Thus, turbine efficiency, $\eta_{turbine}$, can be calculated as follows:

$$\eta_{turbine} = P_{turbine}/(WA_m) \quad (5.5)$$

where $P_{turbine}$ is the power generated by the turbine (in watts), W is the experimental power density of the membrane (in watts per square meter), and A_m is the area of the membrane (in square meters). This calculated value can then be compared to the manufacturer's specification for the turbine efficiency as an assessment of accuracy.

The overall efficiency of the OHE process, η_{OHE}, can also be evaluated by students using the following equation:

$$\eta_{OHE} = P_{turbine}/\Sigma P_{in} \quad (5.6)$$

where ΣP_{in} is the sum of all energy inputs into the system. These inputs will be dominated by the energy required to run the draw solution stripping unit, but other power inlets include the energy required to power the pumps that circulate fluids. Students will be able observe how operating conditions such as applied hydraulic pressure, draw solution concentration, and draw solution temperature, all of which impact the power density of the membrane module, directly impact the overall efficiency of the OHE.

5.3 Bench-Scale System Considerations

A bench-scale PRO system could be adapted to the capstone laboratory with relative ease, based on systems described in previous chapters. As shown in Figure 5.5, the system

would be similar to the mobile forward osmosis system described in Chapter 4 (Anastasio & McCutcheon, 2013). Some alterations include replacing the draw gear pump with a variable speed diaphragm pump capable of delivering pressures up to 300 psi (~20.7 bar), replacing several of the draw solution lines to be more pressure-tolerant, swapping the scale and stir plate under the feed and draw tanks to minimize vibrational readings on the scale, and adding a bypass line to the draw solution line to allow for independent control of pressure and flow rate. Furthermore, to help stabilize the system, bypass lines were added around the cell to allow scale equilibration.

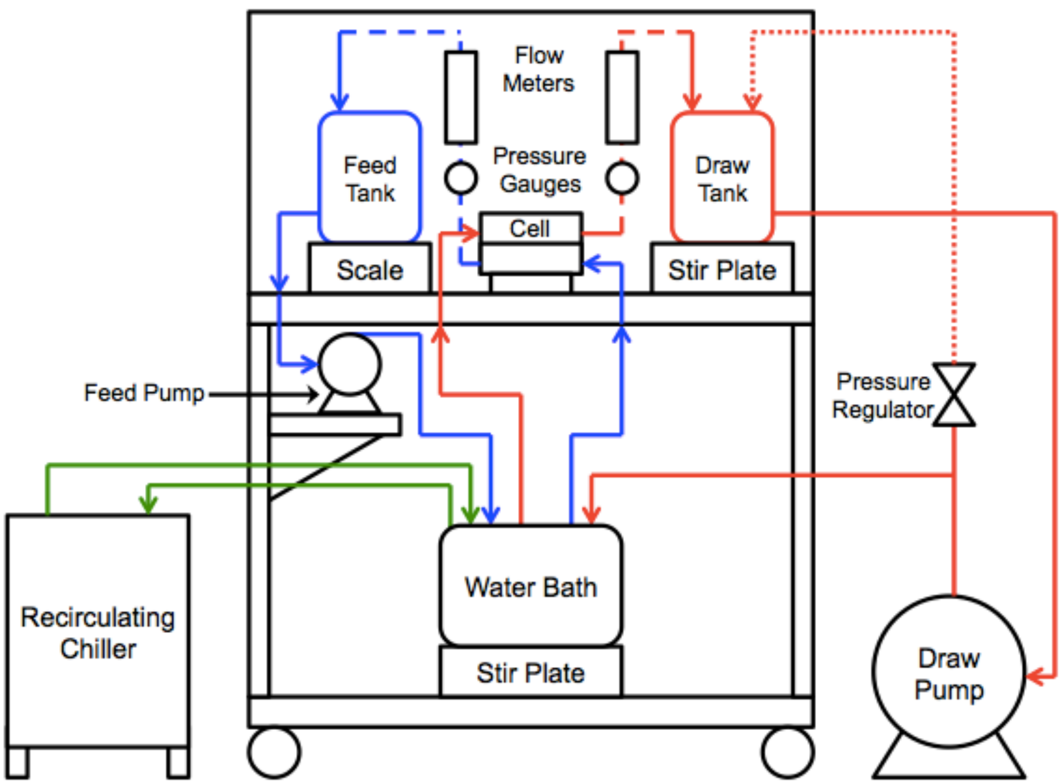

Figure 5.5: Apparatus diagram of a cart-mounted PRO system based on a modified design of a cart-mounted FO system. Dashed lines indicate lines hidden behind a backsplash. The dotted red line represents the draw solution bypass line. Bypass lines around the cell have been omitted for clarity.

While the membrane cell was modified to enable pressurizing one side of the membrane, there are limitations to this new design, shown in Figure 5.6. The spacer mesh packed into the feed channel creates significant pressure drop through the feed side of the

membrane (up to 2 bar). The amount of spacer mesh used to pack the channel also has a profound impact on the cell's ability to seal the membrane. If too much mesh is used, water can leak out of the feed side of the membrane, artificially increasing the water flux. If too little mesh is used, draw solution can leak around the membrane, lowering the effective osmotic pressure gradient and lowering the driving force for water flux. Using too little support mesh may also cause the membrane to fail if it is unable to withstand the applied pressure. Other custom feed-side supports, such as specially machined spacers that support the membrane while minimizing pressure drop, may be used. However, assuring a strong seal around the membrane is vital for generating meaningful data from PRO tests.

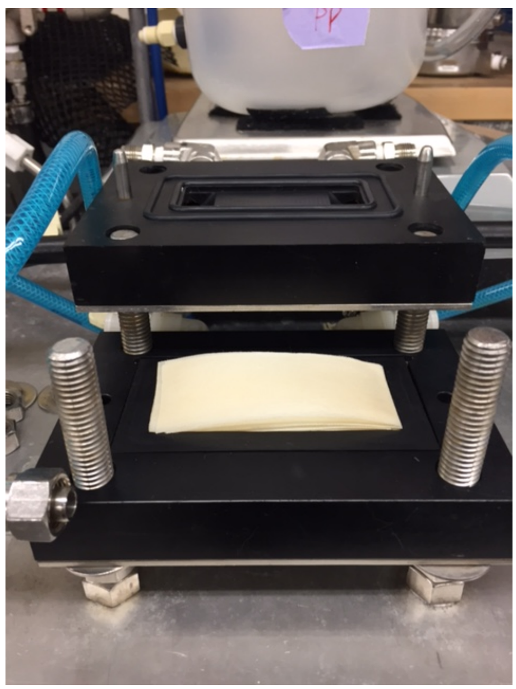

Figure 5.6: Image of PRO cell used in bench-top apparatus. The feed channel is packed with tricot spacer mesh to support the membrane against the pressurized draw solution. The cell is sealed with a gasket around the feed channel and o-rings around the draw channel.

The effect of improper cell sealing is demonstrated in Figure 5.7. In this case, a thin film composite (TFC) provided by Hydration Technology Innovations (HTI) was tested using a 3 M ammonia-carbon dioxide draw solution. This solution was predicted to have an osmotic pressure of approximately 135 bar, and the membrane was determined experimentally to have

a hydraulic permeance of 1.49 L m^{-2} hr^{-1} bar^{-1}. Based on these parameters, and assuming a perfectly selective membrane and neglecting all concentration polarization effects, the power density for this membrane should have been on the order of magnitude of hundreds of watts per square meter of membrane (approximately 700 W/m^2). However, as Figure 5.6 demonstrates, a peak power density of 14 W/m^2 is projected based on the trends in the data. While salt crossover and both internal and external concentration polarization would lower the overall power density of the membrane, a 98% reduction in peak power density is not anticipated when these non-idealities are considered. Solute flux was also high during these tests, averaging 190±40 g m^{-2} hr^{-1}, suggesting possible solute leaking around the membrane from the draw into the feed. Data could not be taken at transmembrane pressures above 15 bar, as water flux would rapidly invert or the concentration of the feed would rapidly spike, indicating an abrupt membrane failure.

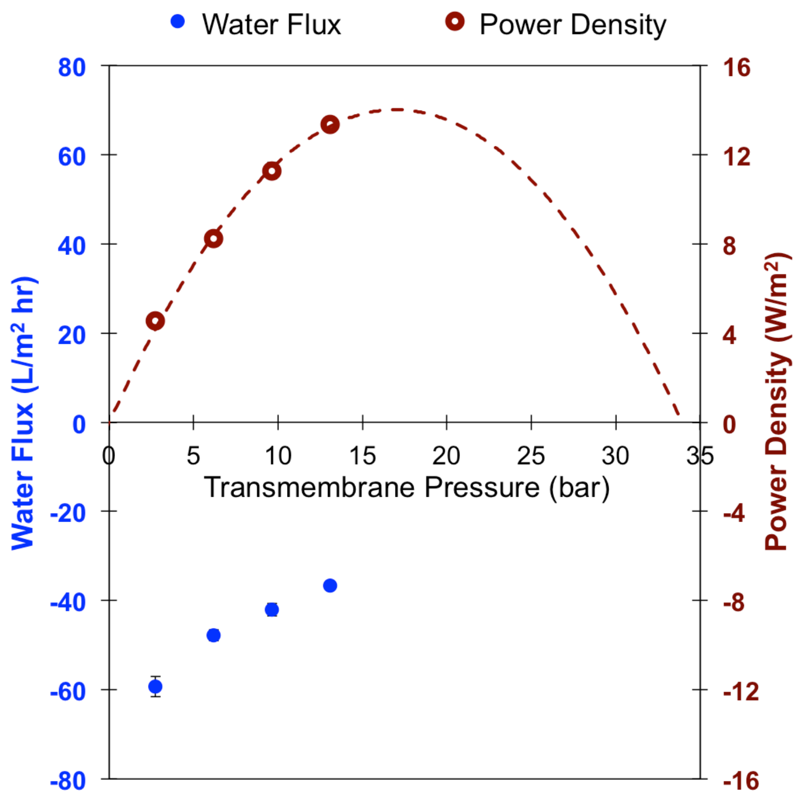

Figure 5.7: Water flux and power density for a bench-scale PRO test using the HTI thin-film composite membrane and a 3 M ammonia-carbon dioxide draw solution at 20 °C. Flow rates were 2 L/min for draw and 1 L/min for feed. The dashed line denotes a quadratic trendline for power density based on the first four experimental data points.

These findings should not imply that bench-scale PRO tests are not worthwhile. The cell was able to seal effectively around the thicker, more durable HTI cellulose triacetate (CTA) membrane. This membrane has a lower hydraulic permeance than the TFC membrane (approximately 0.9 L m-2 hr-1 bar-1) (Cath *et al.*, 2013). However, studies using this membrane with this cell design have yielded statistically significant results (Anastasio *et al.*, 2015), suggesting that a PRO experiment using this membrane, this bench-top configuration, and a sodium chloride draw solution would be a viable student experiment in the teaching laboratory.

5.4 Pilot-Scale Osmotic Heat Engine Considerations

As the pilot-scale OHE system is currently still being constructed as of writing, the following sections are meant to explain why certain parts have been selected for the pilot-scale

osmotic heat engine that is currently being constructed, along with rationale for why other options were not selected, based on information currently available.

5.4.1 Draw Solute Selection

In a closed-loop PRO process, the draw solute must be recovered to maintain a high osmotic pressure gradient between the feed and the draw, which maximizes water flux. Several potential draw solutes for engineered osmosis have been proposed and studied, but the ideal draw solute should be highly soluble and have low energy requirements for removal. Several categories of draw solute have been summarized in Table 5.1.

Table 5.1: Types of draw solutes available for an OHE process

Recovery Method	Description	Examples
Physical Recovery	Solutes recovered by a physical process, including evaporation or filtration	• Ionic solutes • Magnetic nanoparticles
Thermolytic Decomposition	Solutes dissolve into gas when heated and are re-absorbed into new draw	• Ammonium salts • Carbonate salts
Thermal Solubility	Solutes that become immiscible in solution when heated	• Specialty polymers • Certain hydrogels
Distillation	Solutes that are volatile and therefore can be distilled	• Alcohols
Phase Switching	Solutes with solubility that can be manipulated through CO_2-catalyzed acid base reactions	• Switchable polarity solvents

Several of these draw solutions are currently being developed; thus, they are not ready to be used in an OHE at this time (Ou *et al.*, 2013, Stone *et al.*, 2013, Wilson & Stewart, 2014). Furthermore, a physically separable solute, such as sodium chloride via RO, was deemed inappropriate for this study. While an ionic salt may be appropriate for an OHE used for osmotic grid storage, this study requires the recovery of the draw solute using low quality energy. Ultimately, an ammonia-carbon dioxide (NH_3-CO_2) draw solution was selected for this study. The draw solution was selected for its thermolytic nature, its high solubility in water, and the extensive literature available on the subject (McCutcheon *et al.,* 2006, McGinnis *et al.*, 2007, Xu

et al., 2014), as well as its use in an industrial osmotic dewatering process (McGinnis *et al.,* 2013).

5.4.2 Solute Recovery System

The most common method for the solute recovery step with an NH_3-CO_2 draw solution is stripping via a distillation column, illustrated in Figure 5.8 (McGinnis & Elimelech, 2007, McGinnis *et al.*, 2013). In this system, a distillation column is used to strip the ammonia and carbon dioxide gas from the dilute draw solution. The dilute draw is heated in the reboiler and pumped to the top of a distillation column, which can be held under vacuum for increased separation efficiency (McGinnis & Elimelech, 2007). During the stripping, the draw solute decomposes to gaseous ammonia and carbon dioxide and flows out of the top of the column, while dilute water flows out the bottom. A portion of this dilute stream is returned to the feed-side of the membrane, while the rest is sent to a condenser where the gaseous draw solutes are dissolved to form the concentrated draw solution. The primary limiting factors for this design choice are related to the size of the column. Typical stripping columns for a similar process can be multiple stories in height (McGinnis *et al.*, 2013). Furthermore, if portions of the column are not operating at peak tray efficiency, the column must be lengthened further. Size constraints, as well as the energy required to pump the fluid from the reboiler to the top of the column, discouraged this design as a possible option.

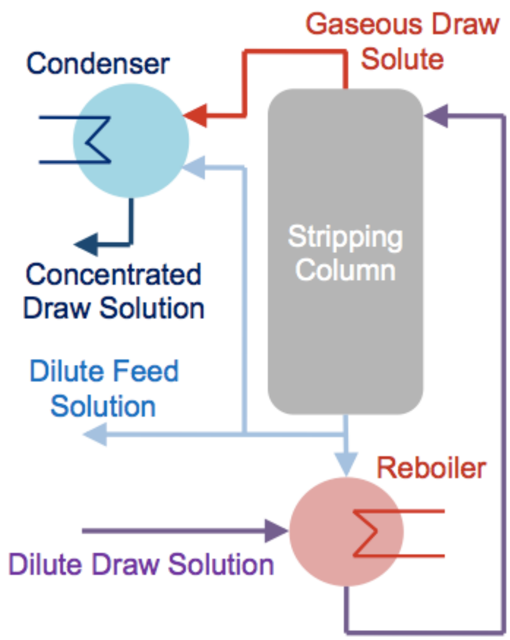

Figure 5.8: Diagram of the ammonia-carbon dioxide stripping column and concentrated feed condenser units.

The method currently being pursued for the stripper-absorber unit, developed by Dr. Robert McGinnis, involves a vertically-mounted shell-and-tube heat exchanger that functions as a falling-film stripper (McGinnis, 2014). The liquid is heated as it travels down the stripper, while a sweep gas of nitrogen flows countercurrent upwards. As demonstrated in Figure 5.9, it is anticipated that the nitrogen will force the dilute draw solution to the sides of the tubes, creating a thin film that will both heat quickly and will have a high interface area for ammonia and carbon dioxide to transfer from the liquid to gaseous phase. A second heat exchanger is placed in series after the stripper, which serves as a condenser and absorber. After the feed solution has been removed, the dilute draw travels to the heat exchanger where it is mixed with the ammonia and carbon dioxide in the sweep gas. The shell-side of the heat exchanger is filled with cooling water, forcing the gases to dissolve back into the draw solution. This configuration has the potential to be less space consuming and use energy more efficiently, as heat is constantly applied as the draw solution passes through the system, increasing the heat transfer rate into the solution.

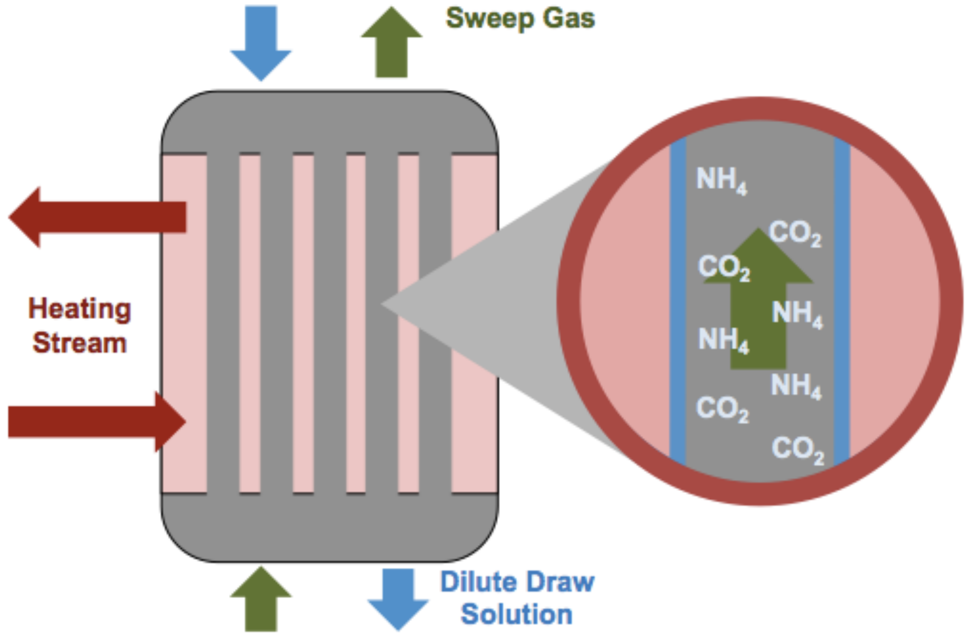

Figure 5.9: Diagram of the falling-film ammonia-carbon dioxide stripper. The inset shows ammonia and carbon dioxide leaving the liquid phase and being carried by the nitrogen sweep gas.

This element of the OHE system provides students with hands-on experience with thermodynamics, phase equilibria, and heat transfer. Beyond flow meters and pressure gauges, several other specialty pieces of instrumentation must be added to the stripper and absorber to allow students to collect the data required for this analysis. Temperature probes should be installed to allow students to monitor inlet and outlet temperatures of all streams. This data will allow students to calculate key heat transfer parameters such as the overall heat transfer coefficient for the stripper and absorber. Furthermore, ammonium sensors should be installed in the stripper inlet, stripper outlet, and absorber outlet lines, to allow students to monitor the concentrations of ammonia before and after passing through the stripper as well as the concentration of the newly created concentrated draw solution. Students can then model the process in Aspen HYSYS using the OLI electrolyte plugin and their experimental flows to verify that their results are accurate. Currently, a group of seniors has been performing the analysis of this system in Aspen successfully, demonstrating that the Aspen simulation could be

an additional component of the OHE laboratory when fully implemented into the laboratory curriculum.

5.4.3 Membrane & Turbine Selection

The membrane selected for this apparatus was dependent upon the draw solution used. As the NH_3-CO_2 draw was selected, the chosen membrane needed to have acceptable tolerance to basic conditions. The previously mentioned HTI TFC and HTI CTA are two of the only commercially available membranes appropriate for forward osmosis (Technology, 2010). Although these membranes are not designed specifically for PRO, they can be operated safely at lower pressures. The HTI CTA membrane hydrolyzes and degrades in basic solutions (Vos *et al.*, 1966), so a TFC membrane module that is 21 inches long and 2.5 inches in diameter has been ordered from HTI. Between the CTA and TFC membranes, the TFC has a higher hydraulic permeance (Ren & McCutcheon, 2014), which will contribute to enhanced power density. The module is anticipated to run at a maximum pressure of approximately 200 psi (13.8 bar) to minimize the chance of damage to the membrane element.

The membrane element will allow students to perform experiments with a full-sized membrane module, rather than just individual coupons in a small channel. Therefore, more elaborate instrumentation is required to allow students to collect the data they need to analyze this system. The increased membrane area means that a much greater volume of water will permeate the membrane. Flow meters must be installed before and after the membranes on both the feed and draw side; differences in flow rates at the inlet and outlet of the membrane module will allow students to calculate water flux. Furthermore, pressure gauges and a means to measure conductivity (either directly via probe or sampling ports to measure conductivity *ex-situ*) are also required, which will allow students to gain an accurate measurement of hydraulic pressure gradient and osmotic pressure gradient, respectively, within the membrane element. Once students have determined water flux, hydraulic pressure gradient, and osmotic pressure

gradient, they can calculate the power density for the condition using the equations stated in section 5.2.

Finally, an appropriately-sized turbine must be purchased to generate power within the OHE. A Pelton wheel turbine is an ideal design for this experiment, as Pelton wheels are typically used in systems where high water pressure head is available but fluid flow is low (White, 2009). Several manufacturers produce Pelton wheel turbines, including The Danfoss Group and PowerSpout, but the challenge is finding a turbine that is appropriately sized for the flows present within the pilot-scale OHE system. If an appropriate vendor cannot be found, fabrication of a Pelton wheel may be required. Agar & Rasi (2008) provide guidelines for the construction of such a turbine, although it must be created of materials that will not corrode or degrade in the presence of the NH_3-CO_2 draw solution.

5.5 Safety Considerations

There are several hazards associated with operating the OHE that students must be cognizant of while performing any experiments using it. Furthermore, appropriate safety features, such as pressure relief valves and vents, must be installed in the event of an emergency. The installation of automatic controllers will assist in making this experiment safe for student use. As this experiment is being built in a high-bay area, students must wear appropriate personal protective equipment, including safety glasses, gloves, laboratory coats, and hard hats. Students must be taught the hazards of the experiment and appropriate responses to emergency situations prior to beginning the OHE experiment.

The primary hazard is exposure to high concentrations of ammonia and ammonium salts, due to both the health hazards associated with ammonia exposure as well as its flammability. While the OHE is anticipated to be closed-loop and have no ammonia discharge to the environment, pressure relief valves with vents must be installed in the event of unexpected over-pressurization of any of the units or storage tanks. As ammonia gas cannot be discharged to the environment directly (Phillips, 1995), these vents must be diverted to a

scrubber to remove the ammonia either with water or a weakly acidic solution. The scrubbing solution may be able to integrate back into the OHE, or it may be safely discarded based on EH&S regulations. In the event of accidental ammonia discharge to the environment, students should be advised to immediately turn off all steam lines and vacate the area.

Another hazard associated with this experiment is the use of steam. Steam not only presents a temperature hazard, but steam condensate discharge may also collect on the floor of the laboratory, presenting a slipping hazard. All steam lines must be insulated to minimize accidental contact, and all discharge lines must be secured within appropriate floor drains.

5.6 Concluding Remarks

A pressure retarded osmosis experiment for chemical engineering students presents applications of osmotic membrane processes in contexts beyond desalination, linking to energy production and sustainability while highlighting a process that may be unfamiliar to students. Furthermore, principles of PRO present a unique link between concepts of mass transport, fluid mechanics, and thermodynamics. While a closed-loop bench-scale system demonstrating water flux is possible using systems similar to those previously developed for the undergraduate teaching laboratory, such would not visually display the power being generated to students and the cell design limits what membranes and draw solutes may be used. As such, a pilot scale demonstration of PRO is preferable using an ammonia-carbon dioxide draw solution to enable low temperature thermal stripping, as it grants students the benefit of working with large-scale equipment. Moreover, the components of the large-scale OHE will allow students to experience multiple chemical engineering unit operations as part of one experiment. However, due to the complexity and hazards associated with the ammonia-carbon dioxide OHE, the pilot-scale system currently being constructed must be tested extensively for robustness, quality of data produced, and safety before students should be allowed to perform experiments as part of the laboratory course. Ideally, control systems should be fully integrated into the system to maintain

safe temperatures and pressures, which would allow students to practice manipulating process controllers at the pilot-scale.

The following chapter presents a bench-scale study of the impact of draw solution concentration and system temperature on the power density of a commercial forward osmosis membrane that was not specifically optimized for high performance in pressure retarded osmosis. The membrane is thick and durable enough to withstand pressures without substantial leaking, and the sodium chloride draw solution is safe for students to work with without additional personal protective equipment beyond the laboratory standard. While elements like a turbine, draw solution recovery, and evaluation of overall engine efficiency are excluded, the experimental apparatus and procedure provide a thorough basis for a PRO experiment that could be performed in the undergraduate laboratory, exposing students to fundamental concepts such as power density and the idea that an osmotic potential can be converted into work.

CHAPTER 6

EXAMINING THE IMPACT OF OSMOTIC PRESSURE ON WORK GENERATED BY A CLOSED-LOOP PRESSURE RETARDED OSMOSIS PROCESS

Originally published as:
"Impact of Temperature on Power Density in Closed-Loop Pressure Retarded Osmosis for Grid Storage"
by D. Anastasio, J. Arena, E. Cole, & J. McCutcheon
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6.1 Introduction

The adoption of many carbon-neutral and renewable power technologies, such as solar or wind power, has been hindered by intermittent availability and intensity. Currently, these problems are being addressed by the development of grid storage techniques for excess power, permitting the distribution of energy during periods of high demand and energy storage during times of low demand. Batteries, compressed air, and water reservoirs have all been considered for grid storage applications, but each technology has drawbacks of either being prohibitively expensive or logistically difficult to implement (Cavallo, 2007).

With the advent of engineered osmosis (EO) processes, a radically different concept for grid storage has emerged based on the concept of pressure retarded osmosis (PRO) (Loeb, 1976, Loeb *et al.*, 1976, Achilli *et al.*, 2002). In times of energy scarcity, a PRO membrane module can be run using a concentrated solution, known as the draw, and a dilute solution, known as the feed. The draw solution is pressurized, and when water naturally flows from the dilute stream into the concentrated stream, the volume of the draw increases and work is performed. This work can be used to turn a turbine and produce electricity. Energy from a secondary source, such as waste heat or geothermal energy, can be used continuously to recover the draw and feed solutions. If energy is not available, the solutions can be stored indefinitely until energy is available for recovery.

When energy is used to concentrate the draw solution, that energy is stored in the form of osmotic potential indefinitely (Robinson & Stokes, 2002). Depending on the properties of the chosen draw solute, the solute recovery method can vary widely. It can be be multistage distillation or gas stripping for thermolytic solutes, or reverse osmosis and membrane distillation for non-volatile solutes (McCutcheon *et al.*, 2007). For an osmotic *heat* engine, the energy used is thermal energy which can be used to strip a thermoytic solute *or* evaporate water to concentrate the solute. These concentrated draw solutions will not lose osmotic potential if properly stored, and the potential can be easily increased with additional solute (McGinnis & Mandell, 2011). These features overcome many of the limitations of other grid storage methods. Furthermore, higher water flux in the PRO step will lead to increased energy released, leading to a more efficient overall process. This closed-loop energy conversion process illustrated in Figure 6.1 is known as the osmotic heat engine (OHE) (McGinnis *et al.*, 2007). It is important to note that, in the case of the grid storage option outlined in Figure 6.1, the solute recovery system is only run to recover the draw and feed solutions when excess base-load power is available. In time of high energy demand, the solute recovery system is not run, and the stored feed and draw solutions are used by the PRO membrane element to generate power.

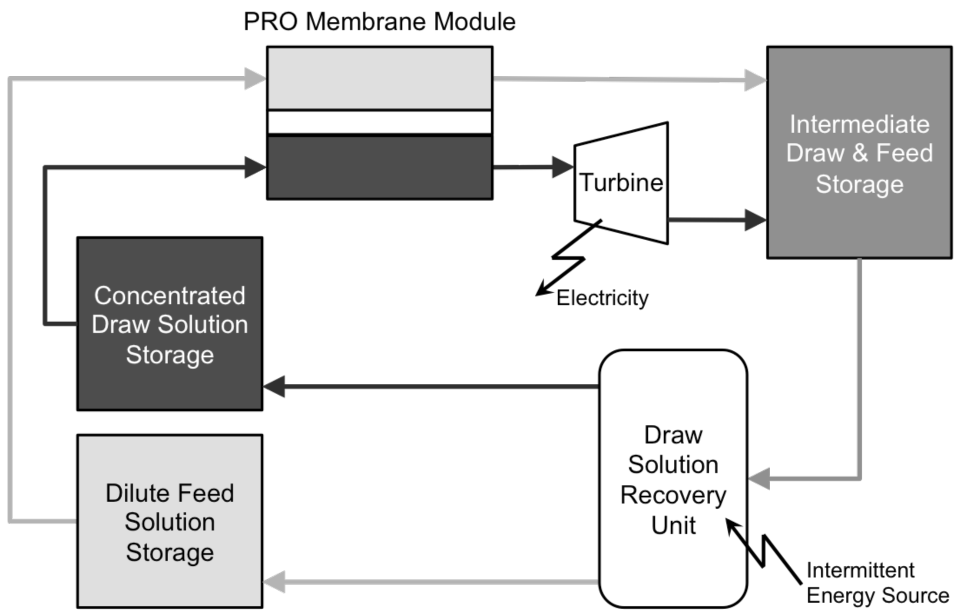


Figure 6.1: Schematic for an osmotic heat engine used as part of an osmotic grid storage system. The draw solution recovery unit operates when energy is available, and the PRO membrane module operates when energy is in demand (pressure exchanger to maintain draw solution pressure is not shown).

The OHE consists of three subsystems. The solute recycling system converts the power generated by the intermittent energy source into osmotic potential. The membrane process converts the osmotic potential into hydraulic potential. The hydroturbine converts the hydraulic potential into an electrical current, generating power. These subsystems are at various levels of development as established technologies. The methods of draw solution recovery are generally conventional separations processes that are well developed for similar processes. Likewise, hydroturbines are a mature and understood technology.

The membrane process, however, has only on rare occasions been demonstrated. Many of the "studies" were never published in the literature and only a handful of benchtop studies with flat sheet membrane coupons have been published. It is critical to analyze this part of the system under relevant PRO conditions, though, since the amount of energy released during this step is related directly to the energy generating capability of the integrated system.

We often characterize this system by considering the “membrane power density”. This power (or work, *W*, reported in watts per square meter of membrane area) is the maximum power available to a hydroturbine. (Lee *et al.*, 1981, Achilli & Childress, 2010). It can be calculated based on equation 6.1.

$$W = \eta J_w \Delta P \quad (6.1)$$

In this equation, η represents the turbine efficiency, which is often assumed to be 1 when evaluating membrane performance. When this equation is combined with the general water flux equation for EO, the maximum possible power density for any PRO process is generally determined as $A[(\Delta\pi^2)/4]$, where A is a membrane property known as the hydraulic permeance, and $\Delta\pi$ is the effective osmotic pressure gradient between the feed and draw solutions (McGinnis & Elimelech, 2008, Cath *et al.*, 2006). Therefore, assuming no mass transport limitations imposed by concentration polarization (CP) (McCutcheon & Elimelech, 2006, McCutcheon & Elimelech, 2007), peak power density is a function of both osmotic pressure and membrane permeance. While osmotic pressure will increase with draw solute concentration, both osmotic pressure and hydraulic permeance will increase with temperature. These parameters can be tightly controlled in OHE operation, which potentially yields power densities that are not possible using PRO with seawater as the draw solution, also known as open-loop PRO (Yip & Elimelech, 2012). The manipulation of temperature and draw concentration beyond what may occur naturally can improve the viability of osmotic energy storage using membranes that had previously been considered not suitable for PRO due to their low power density.

This study was conducted to measure the water flux and power density produced by a commercial FO membrane operated under high-concentration and elevated-temperature conditions similar to those present in an OHE. In order to assess the accuracy of the experimental results, the data was then compared to predictions generated by an established model for PRO performance. We demonstrate that even membranes that are not specifically

designed for PRO applications can still operate at high power density in conditions similar to that of an OHE. This finding is relevant to OHE development because, while high flux engineered osmosis membranes are currently reported in literature, there is currently no commercially available membranes or membrane module designed specifically for PRO applications. Being able to achieve high power density with less permeable but more commercially available membranes would enable the construction of a functional OHE.

6.2 Materials & Methods

6.2.1 Materials & Chemicals

The cellulose acetate (CA) membrane used in this study was provided by Hydration Technology Innovations (HTI^{TM}, Albany, OR). The membrane is composed of a cellulose acetate active layer with an integrated woven mesh support layer. These membranes have been used as a benchmark in prior studies of FO (Cath *et al.*, 2013). Water was provided by an Integral 10 water system (Millipore Corporation, Billerica, MA).

Sodium chloride was purchased from Fisher Scientific (Pittsburgh, PA). Sodium chloride was selected as the test draw solute for this study. While sodium chloride would not be an ideal solute in an actual OHE, the draw solutes can still be thermally recovered by evaporation or physically recovered by reverse osmosis. Sodium chloride was also selected for this study because it is highly soluble and stable in water. Therefore, high draw solute osmotic pressures are possible at a wide range of concentrations and temperatures. Furthermore, sodium chloride was also used in the previously mentioned characterization study (Cath *et al.,* 2013), which provides a point of comparison for the current study.

6.2.2 Bench-Scale PRO system

A benchtop PRO system was used to measure water flux and salt flux under true PRO conditions on the coupon scale. Both the feed and draw solution were temperature controlled using a recirculating chiller/heater (Fisher Scientific, Waltham, MA). Draw, feed, and draw bypass streams were circulated counter-currently though a custom membrane cell with channel

dimensions of 3 inches long by 1 inch wide by 1/8 inch deep (7.6 cm by 2.5 cm by 0.3 cm), similar to the cell dimensions described in another paper by the authors (Anastasio & McCutcheon, 2013). The feed channel was completely filled with several layers of pre-wet Tricot mesh support in order to prevent membrane deformation when the draw solution is pressurized. The membrane was sealed in the cell using a PVDF gasket (McMaster, Princeton, NJ) around the channel on the feed half of the cell and a PVDF o-ring (McMaster) embedded around the channel on the draw side of the cell. A proper seal with the correct amount of tricot ensured that the cell would not leak and that the membrane would not be bypassed. Water flux was measured gravimetrically using a balance (Denver Instruments PI-4002, Denver Instruments, Bohemia, NY) and data acquisition software. A conductivity probe and thermometer were placed into the feed tank to monitor solution conductivity and temperature. A diagram of the complete system is located in Figure 6.2.

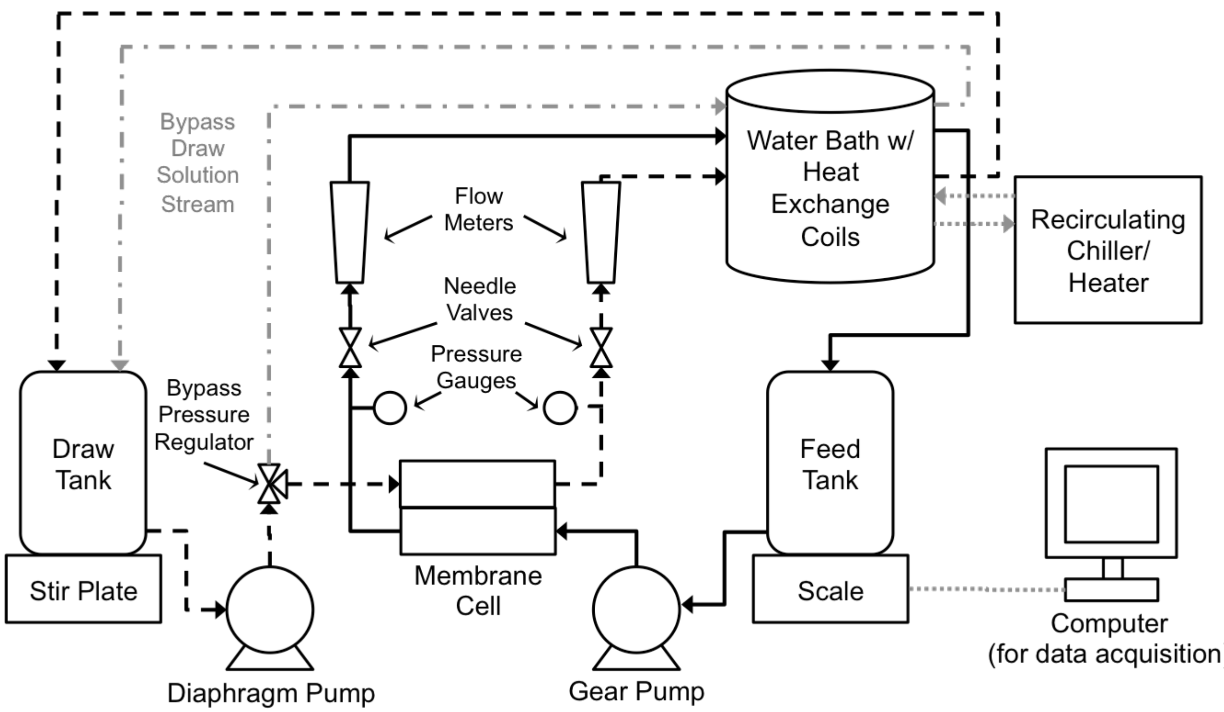


Figure 6.2: Schematic of the bench-top PRO system

Fresh membrane samples were tested in triplicate using the PRO orientation (described elsewhere as AL-DS) (Gray *et al.*, 2006) and evaluated at two temperatures: 20 ºC and 40 ºC

(for both draw and feed solutions). At each of these temperatures, three draw solutions of 0.5 M, 1.0 M, and 1.5 M sodium chloride (NaCl) were tested. The feed stream was deionized water for all tests. Stream flow rates for the feed and draw were maintained at 1 L/min (0.25 m/s) and 2 L/min (0.5 m/s), respectively. For each draw solution, pressure was increased from 3.45 bar (50 psi) to 20.6 bar (300 psi) in 3.45 bar increments. Once maximum pressure was achieved, the pressure was then reduced in 3.45 bar increments to assure that flux had not changed as a result of high-pressure membrane deformation. Each pressure was maintained for 10-15 minutes while data was collected. Feed solution conductivity was measured following each change in pressure.

6.2.3 Determination of Model Parameters

The experimental data was compared to data generated using the equation derived by Yip and Elimelech (2011) in order to assess its accuracy. The model accounts for both concentrative and dilutive external concentration polarization (ECP) on the feed side and draw side of the membrane, respectively, and concentrative internal concentration polarization (ICP). As ICP is usually the greatest mass transport limitation in osmotically-driven flow across asymmetric membranes in most closed-loop PRO processes, ECP on the feed side can be neglected if feed concentration is low (Cath *et al.,* 2006). The model generated water flux and power density data assuming constant draw solution concentration and negligible feed solution concentration. Mass transfer coefficients for the solutions were determined using Reynolds, Schmidt, and Sherwood number correlations (Mulder, 1996, Geankoplis, 2003).

Reverse osmosis (RO) tests of the HTI CA membrane were performed to evaluate hydraulic permeance (*A*) and solute permeability (*B*) membrane at both 20°C and 40°C, as both *A* and *B* are expected to increase as temperature increases. Membranes were tested in a lab-scale crossflow RO system at a cross-flow velocity of 0.25 m/s. The channels of the membrane cells had the same dimensions as the channel in the PRO membrane cell. The system design is described in a previous paper by the authors (Anastasio & McCutcheon, 2012). RO tests

were conducted with fresh membrane samples operating at temperatures of 20°C and 40°C. To measure water permeance, water flux through the membranes was collected at pressures of 8.6, 15.5, 22.4, and 29.3 bar. Salt rejection tests were conducted with a feed of 2000 parts per million (ppm) sodium chloride at a pressure of 15.5 bar. The conductivity of permeate and feed were measured to determine the rejection. Solute permeability for the membrane was determined using the water flux and intrinsic rejections for the RO test.

Calculated structural parameter (*S*) values were taken from a multiple-laboratory characterization of the FO membrane used in this study (Cath *et al.,* 2013). While the tests in that previous study were performed at 20°C, these *S* values will be valid at any temperature, as *S* depends on membrane characteristics that are independent of temperature (McCutcheon & Elimelech, 2007, Loeb *et al.*, 1997). The previous study reported structural parameters that ranged from 425 to 675 μm, so these values were used to determine a high flux (*S* = 425 μm) and low flux (*S* = 675 μm) condition for the performance of these membranes. The experimental data should fall in the area between the high flux and low flux curves.

6.3 Results & Discussion

6.3.1 Water Permeance & Salt Permeability

Water permeance and solute permeability data are shown in Table 6.1 for all of the temperatures evaluated in this study.

Table 6.1: *A* and *B* parameters for HTI FO membrane based on RO tests with 2000 ppm sodium chloride feed

Temperature (°C)	Water Permeance, *A* (LMH/bar)	Solute Permeability, *B* (LMH)
20	0.589 ± 0.009	0.319 ± 0.041
40	1.12 ± 0.05	0.580 ± 0.119

As anticipated, increasing temperature caused both *A* and *B* to increase since as temperature increased, both water and solutes permeate the membrane more easily. The increase between the two temperatures is significant based on the standard deviation error limits. The 20°C values are also within the range reported previously (Cath *et al.*, 2013).

6.3.2 PRO Performance

Figure 6.3 summarizes the water flux data for 0.5 M, 1.0 M, and 1.5 M NaCl draw solutions at 20°C and 40°C tested under actual PRO conditions. It is important to note that a positive flux is denoted by water traveling from the draw solution into the feed. Thus, a negative flux is reported when water travels from the feed to the draw and is desirable for PRO.

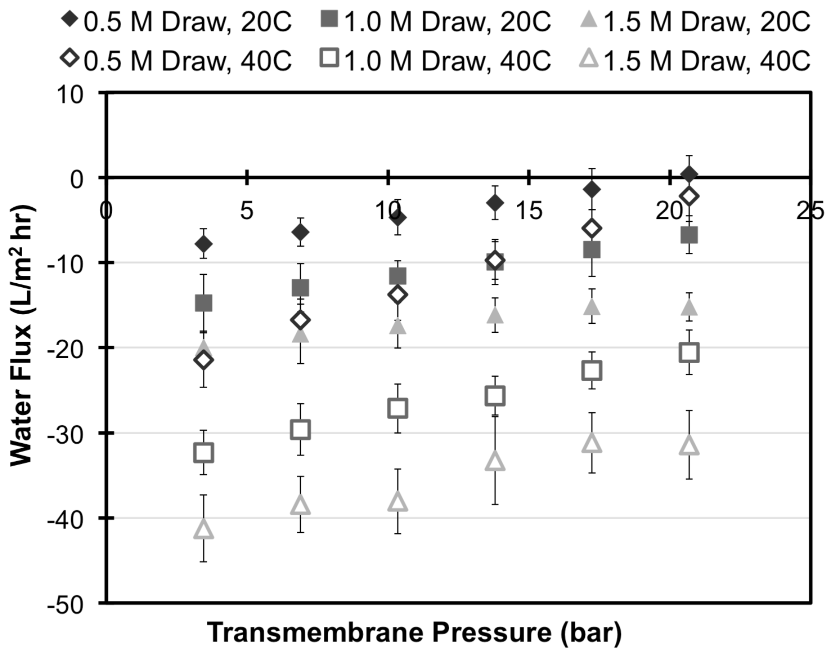


Figure 6.3: Experimental water flux of the HTI cartridge membrane as a function of draw solution pressure for 20 and 40 ºC and draw solution chemistries. Draw solute was sodium chloride. Draw flow velocity was 0.5 m/s, Feed flow velocity was 0.25 m/s. Error bars indicate standard deviation of three trials.

Water flux increased with increasing draw solution concentration (higher driving force) and temperature (higher water permeance, enhanced mass transfer. As hydraulic pressure was increased for all temperatures and concentrations, the net water flux decreased. This trend is expected based on equation 6.1.

Figure 6.4 illustrates power density as a function of draw solution pressure for the three draw solutions at 20 ºC and 40 ºC. At constant temperature and concentration, increasing hydraulic pressure causes power density to increase and reach a maximum. This peak power density is visible in the data for the 0.5 M draw solutions. At constant pressure, conditions that

yield high net water flux (either high draw solution concentration or high temperature) also yield high power density.

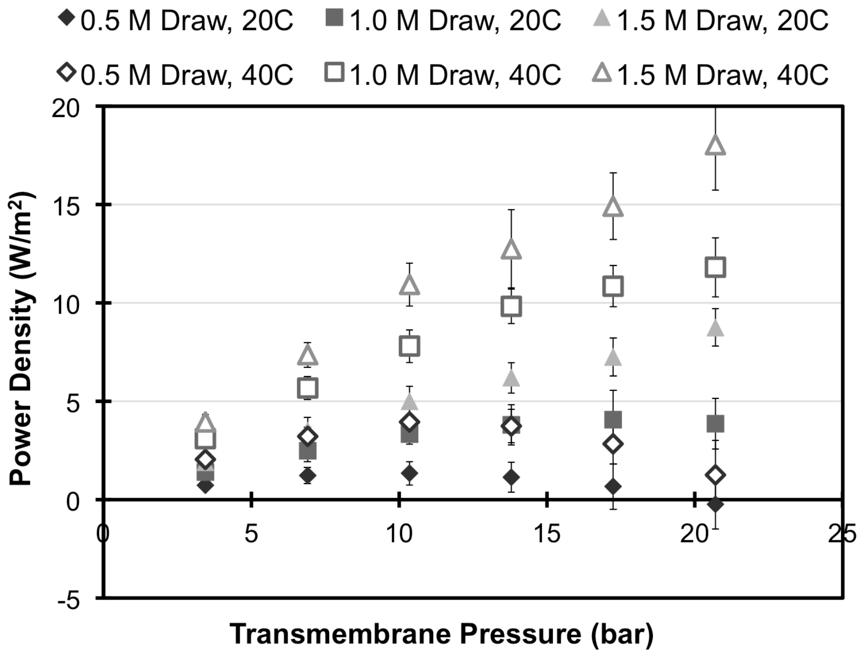


Figure 6.4: Experimental power density of the HTI cartridge membrane as a function of draw solution pressure for 20 and 40 ºC for various draw solution compositions. Draw solute was sodium chloride. Draw flow velocity was 0.5 m/s. Feed flow velocity was 0.25 m/s. Error bars indicate standard deviation of three trials.

The 0.5 M draw solution data has an interesting feature. A flux inversion point occurs, indicating the pressure at which osmotic equilibrium exist and the process transitions from PRO to RO. Equation 6.1 predicts that this will occur when the hydraulic pressure applied equals the osmotic pressure of the draw solution. However, this data shows otherwise. The bulk draw solution has an osmotic pressure of approximately 24.3 bar at 20 ºC and 26.0 bar at 40 ºC. The actual flux inversion point for the experimental data is approximately 20.5 bar at 20 ºC. For the 40 ºC, the data was extrapolated to estimate a flux inversion point at 22.5 bar. Both of these flux inversion points are substantially lower than expected values.

This discrepancy is explained by salt crossing the membrane. While this salt does not contribute to the osmotic pressure, a more substantial problem is internal concentration polarization, which increases the salt concentration on the opposite side of the selective layer.

At zero flux, salt is free to diffuse through the selective layer and accumulate in the support layer. This effect dramatically lowers the transmembrane osmotic pressure and thus lowers the pressure at which peak power density and osmotic equilibrium occurs (Bui & McCutcheon, 2014).

Salt flux into the feed is shown as a function of operating pressure for 20°C in Figure 6.5(a) and for 40°C in Figure 6.5(b). Although the differences between the data sets are not statistically significant based on the large error bars. Even so, there are general upward trends in salt flux with increasing applied pressure. The upward trend in salt flux generally becomes more visible as the draw solution concentration increases. This trend is likely caused by reduced dilutive ECP in the draw solution as net water flux decreases. Lower water flux into the draw solution would diminish the dilutive ECP boundary layer, which would cause the concentration at the draw-side membrane interface to increase. The resulting change in interface concentration would case greater reverse salt flux into the feed solution. Additionally, at elevated temperatures, greater salt fluxes are likely observed due to the increased salt diffusivity. Higher diffusivity allows the salt to permeate the membrane more readily than it would at lower temperatures.

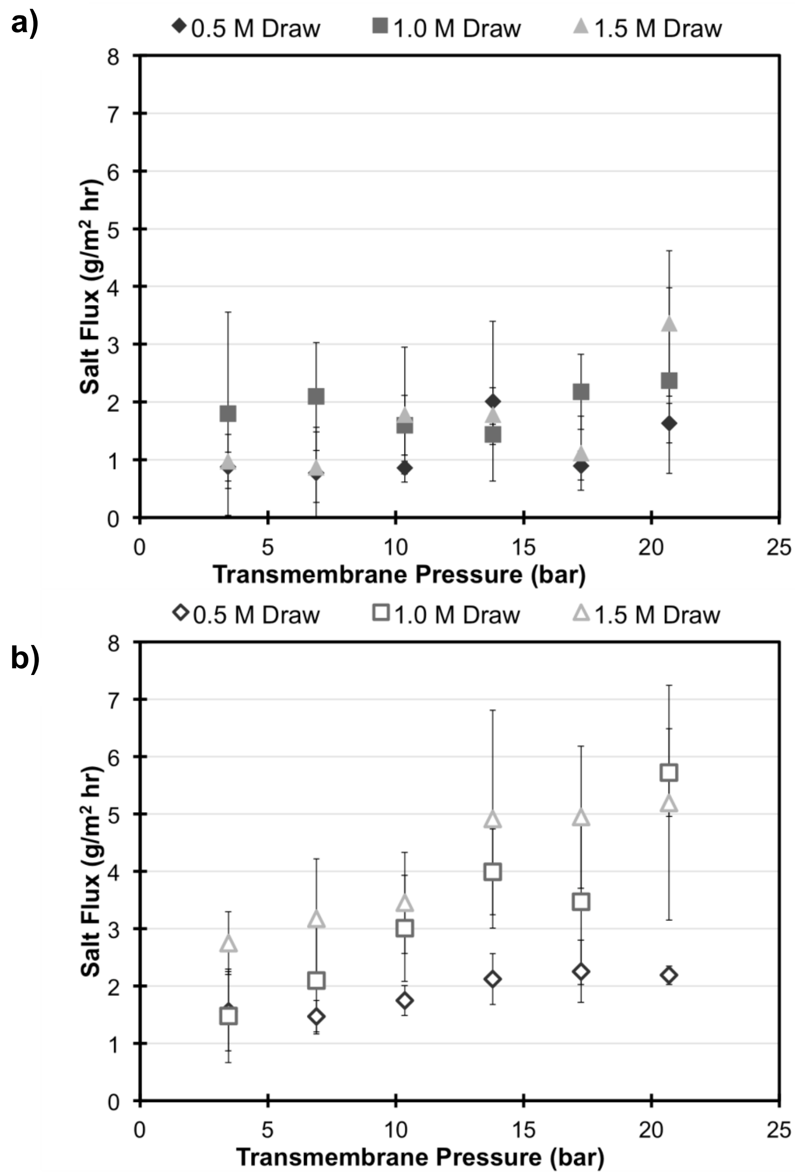


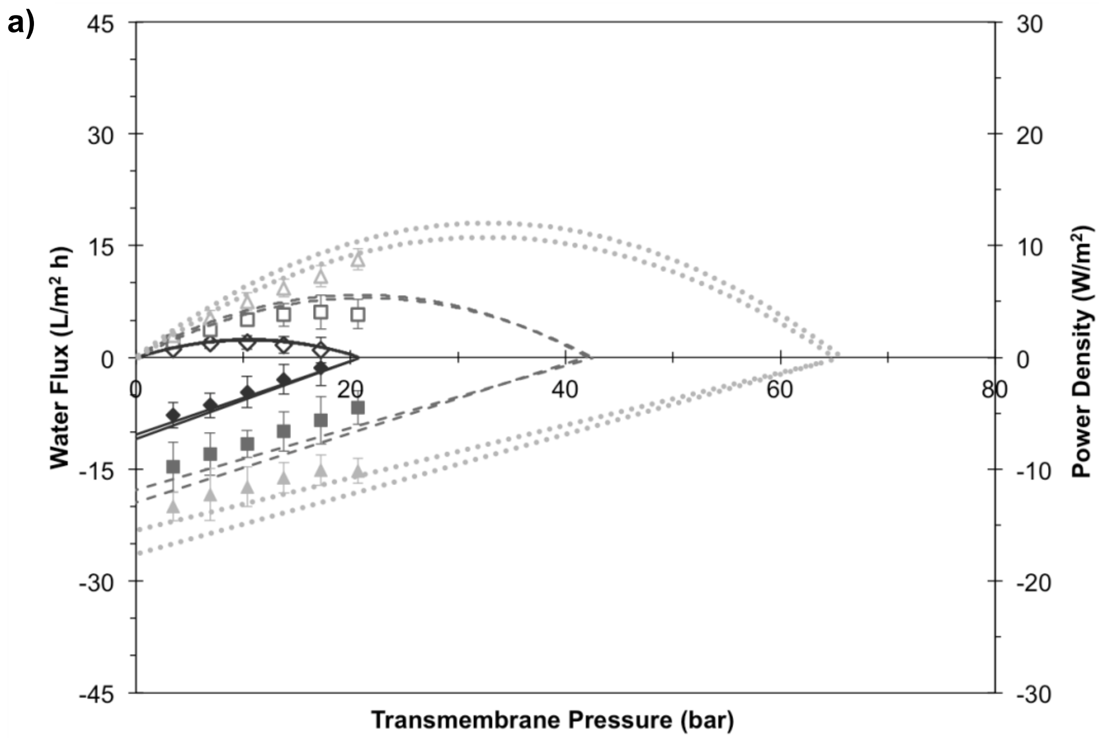
Figure 6.5: Observed average salt flux for the HTI cartridge membrane at 20 ºC (a) and 40 ºC (b) for 0.5, 1.0, and 1.5 M draw solutions at various pressures. Salt was sodium chloride. Draw flow velocity was 0.5 m/s. Feed flow velocity was 0.25 m/s. Error bars indicate the standard deviation of three trials.

6.3.3 Comparison of Simulated and Experimental Data

A comparison of the experimental and simulated data for all tested draw solutions at 20°C and 40°C is shown in Figure 6.6. Experimental flux data is indicated by solid points, and experimental power density is indicated by hollow points. Each data set has two lines predicting the performance of the membrane in PRO under the same temperature and solution conditions.

The lower flux and power density predictions (both closer to the x-axis) are made using the high structural parameter value (S = 675 μm). The other prediction lines, which are both further from the x-axis, assumes a low structural parameter (S = 425 μm). The lines represent different concentrations of draw solution (solid lines representing 0.5 M, dashed lines representing 1.0 M, and dotted lines representing 1.5 M).

The trends in the data are supported by the predicted equation proposed by Yip & Elimelech (2011). Some offset in the data can be explained by small, systematic variations in the system, small differences in the coupons themselves, or feed channel support compaction. As draw pressure increases, the membrane is forced against the tricot support, which may reduce the area of the membrane available for flux. This area reduction will reduce the observed water flux and observed power density, which may explain the lower experimental power density.



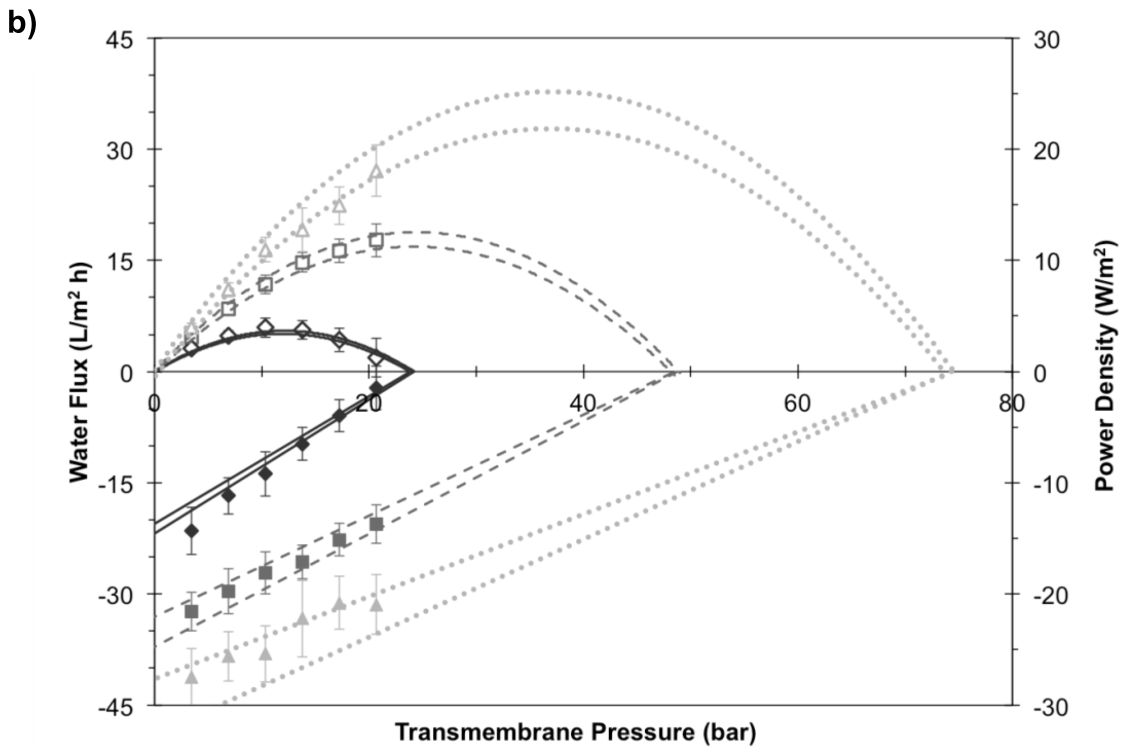


Figure 6.6: Model and experimental water permeability (solid points) and power density (hollow points) at 20 °C (a) and 40 °C (b). Lines indicate the model and points indicate experimental data. Error bars are standard deviation. Diamond points and solid lines indicate 0.5 M draw, square points and dashed lines indicate 1.0M draw, and triangle points and dotted lines indicate 1.5 M draw. Area between the lines indicates range of anticipated values.

In general, operating at a higher temperature yields substantially higher power densities. For instance, the model predicts greater power density at elevated temperatures, as membrane hydraulic permeance, solute diffusivity, and draw osmotic pressure all increase with temperature. The data shows that peak experimental power density of the 0.5 M sodium chloride draw solution change from 1.3 ± 0.6 W/m^2 at 20°C to 4.0 ± 0.9 W/m^2 at 40°C, which is approximately a 300% increase in power density. The effect of temperature is more pronounced at greater draw solution concentrations. For the 1.5 M sodium chloride draw solution, the peak experimental power density is elevated from 8.8 ± 1.0 W/m2 at 20°C to 18.0 ± 2.3 at 40°C. However, these power densities were observed at a hydraulic pressure of 20.7 bar, which is the limit of the bench-top system and far from the peak power density predicted by the equations. If operated at peak power density with a 1.5 M draw solution, the predictions shown in Figure 6 indicate that this membrane could produce up to 12.5 W/m^2 at 20°C and up to 25.0 W/m^2 at 40°C.

The data suggests that high power density PRO is possible with currently available FO membranes, provided they are operated at elevated temperature and pressure. The use of membranes with greater inherent hydraulic permeance (such as a thin-film composite membrane) will naturally yield even higher power density. However, the OHE operating conditions show promise for the future of osmotic power, allowing membranes that were not designed expressly for PRO to exhibit high power density.

6.4 Concluding Remarks

The recent decline in industrial interest in seawater-river water open-loop PRO is a revealing story. Fouling from natural waters, limited osmotic pressure in seawater, and geographic restrictions are all substantial, and perhaps insurmountable, obstacles to this type of osmotic power. The OHE avoids all of these limitations, requiring either low temperature heat or an intermittent renewable energy source, to operate. In this work, we have successfully demonstrated typical conditions of OHEs will in fact produce far higher power densities than

conventional open-loop PRO using a commercially available FO membrane. Future work on this subject will further prove that a system like the OHE, which decouples the PRO step and the draw solute regeneration, may in fact also be useful for grid storage applications. To make such an osmotic grid storage system a reality, the obstacles such as overall process efficiency must be overcome. While membrane selectivity and robustness must be improved to yield high power density, system and module design and draw solution recovery strategies must also be established for appropriate energy sources. Further studies with other draw solute options, such as those able to be recovered thermally, is necessary to determine how these solutes will perform in similar conditions, but the general trends in the data are expected to be similar.

CHAPTER 7

TEACHING REACTOR DESIGN AND SIMULATION USING ADDITIVE MANUFACTURING

Prepared for submission as:
"Print-Your-Own-Reactor: A Reactor Design Experiment Using Rapid Prototyping"
by D. Anastasio, A. Kadilak, J. Arena, J. McCutcheon, L. Shor, & D. Burkey
to *CEE – Chemical Engineering Education*

7.1 Introduction

Additive manufacturing has received a surge in interest in the wake of newer and more affordable 3D printers on scales that range from industrial to desktop that can print a variety of materials (Lipson & Kurman, 2013, Campbell *et al.*, 2011, Kruth *et al.*, 1998). The impacts of these printers are far reaching, allowing for the manufacture of parts both mechanical and biomedical (Berman, 2012, Mironov *et al.*, 2003, Hockaday *et al.*, 2012, Melchels *et al.*, 2012, Denhoff, *et al.*, 2013). Given the increasing attention 3D printers are receiving, many university-level engineering programs are beginning to find new ways to incorporate additive manufacturing principles into their curricula, allowing students to experience these new printers while additionally giving them experience with computer-assisted design (CAD) software.

While it may be relatively easy for programs specializing in mechanical engineering or materials science and engineering to incorporate 3D printers because of an emphasis on the design of parts and materials, it is less obvious how 3D printing could fit into a teaching laboratory curriculum for chemical engineers, who typically specialize in designing processes. However, another unique aspect of 3D printing is the concept of rapid prototyping, where components can be designed, built, and tested relatively quickly and inexpensively (Choi & Samavedam, 2001). As such, these printers can enable experiments in teaching laboratories that allow students to design a small device, model the device to predict its performance, print the device using a commercial desktop 3D printer, and test the device to verify that

performance. Students can then use this information to quickly redesign the device and repeat the tests to verify that improvements were made. This iterative design approach is a critical skill for any engineer, regardless of discipline (Cobb *et al.*, 2003, Dym *et al.*, 2005). The printed devices can teach students about core chemical engineering concepts while allowing them to practice this iterative design process.

One potential printable device involves the construction of a millimeter-scale channel embedded in a larger chip or disk. The concept of using 3D printers to produce milliliter-scale channels has been shown to have numerous applications, from quantification of blood components to chemical synthesis (Chen *et al.*, 2014, Kitson *et al.*, 2012). In this experiment, these channels serve as the reactor for a reaction kinetics experiment, where students evaluate how the design of their printed channels impacts the overall conversion of reagents. Students can then redesign and reprint their reactors quickly and cost-effectively in an attempt to achieve greater conversions.

Although these millimeter-sized channels are not of the same scale as those typically fabricated for microfluidic devices, this experiment draws on many concepts related to microfluidics, as fluid flow is restricted to the laminar flow regime. Several other microfluidics experiments have been developed for the undergraduate chemical engineering instructional laboratory that introduce students to the properties of microfluidics while teaching microfabrication techniques involving casting PDMS over a master prepared using photolithography (Jablonski *et al.*, 2010, Pety *et al.*, 2011, Archer, 2011). While these experiments can fabricate channels on the micron scale, the 3D printer allows for an alternative device fabrication technique where a fully formed channel is prepared, and no additional steps are required before the device is ready to use. Some other benefits of printing millifluidic devices include device fabrication without requiring a clean room and a rigid channel structure that prevents collapsing or rupturing.

The laminar flow regime also imparts an additional design challenge for the students as they consider a chemical reactor. Traditionally, undergraduate chemical engineering students are exposed to continuous stirred-tank reactors (CSTRs) or plug-flow reactors (PFRs) in their reaction kinetics classes. These reactors are relatively simple for students to understand, but many students may take for granted that not all reactors achieve the perfect mixing these models assume. To optimize conversion in the printed laminar flow reactor, students must design their reactors in a way that promotes diffusive mixing, as increased mixing will lead to greater conversions. As such, students must synthesize data from multiple chemical engineering courses to effectively iterate their design. Students will learn that, in the laminar flow regime, channel width is just as important as channel length in terms of overall conversion in a chemical reactor.

7.2 Laboratory Overview

This experiment allows students to design, fabricate, and test multiple milliliter-scale laminar flow reactors. Students are introduced to the concept of rapid prototyping; devices are manufactured relatively quickly and inexpensively using a 3D printer, and designs can then be rapidly iterated for improved performance. In this case, students are tasked to design, model, print, and test a laminar flow reactor. After analysis, students must then design a second reactor that will provide higher conversions than their first reactor. Students are encouraged to achieve the higher conversions through reactor design aspects, such as reactor width and length, rather than simply altering the flow rates. This procedure allows students to treat the dimensions and layout of their reactors as experimental variables. Reactors are designed using the CAD software SolidWorks and modeled in COMSOL Multiphysics, giving students experience with a wider array of software packages.

As laminar flow reactors are typically not part of an undergraduate kinetics course, many students may approach the experiment by trying to solve for conversion as if the printed reactor

is a PFR, using the following equation for conversion in a PFR with a second-order reaction (Fogler, 2006):

$$X = \frac{t_{res}kC_{A0}}{1+t_{res}kC_{A0}} \quad (7.1)$$

where X is conversion, t_{res} is the residence time in the reactor, k is the rate constant, and C_{A0} is the initial concentration of reagent A. While students can use equation 1 to predict conversion, the prediction will be inaccurate due to the assumption of plug flow and perfect axial mixing, which is not possible given the small geometry of the printed reactor. While it is possible to predict the conversion of laminar flow reactors directly and mathematically, the analysis can become complicated for undergraduates who are not familiar with more advanced kinetics concepts such as residence time distributions (Fogler, 2006, Schmidt, 2005). As such, the experiment is presented as a link between reaction kinetics and mass transport, as understanding mass transport concepts will allow students to promote diffusive mixing to achieve greater conversions. Since this reactor is limited to the laminar flow regime, this mixing is primarily achieved through diffusion. Thus, students are given practical laboratory experience with concepts such as diffusivity and Peclet number.

The reaction selected is a saponification of isopropyl acetate using sodium hydroxide, shown below:

IPOAc + NaOH → NaOAc + IPOH

where IP indicates an isopropyl group, Ac indicates an acetyl group, and OH indicate a hydroxyl group. This reaction is second-order, endothermic, and is generally irreversible. This reaction was selected for this experiment because students at the University of Connecticut (UCONN) have already performed batch and CSTR experiments with the reaction in their junior-level laboratory course. As students are already familiar with the reaction, the mass transport and fluid mechanics elements of the experiment can be emphasized. The kinetic parameters, such as the rate constant at various temperatures, have been extensively documented in literature as

well for students who have not performed a batch reaction experiment (Jones & Thomas, 1966, Olsson, 1925, Bamford *et al.*, 1972). Other reactions may be used, provided the chemicals are compatible with the 3D printer resin material that will comprise the reactor.

As students do not use equations to determine the conversion in their laminar flow reactors, COMSOL is used in order to validate the results that are generated experimentally. Using reactor geometries that students can import directly from files generated in SolidWorks, COMSOL is able to predict reactant conversion at the outlet of the device while also reporting fluid velocity and concentrations throughout the device. This experiment provides students with experience setting up COMSOL models in terms of laminar fluid flow and transport of diluted species; furthermore, students learn how to set global parameters in COMSOL and define parameters for a chemical reaction.

7.3 Materials

7.3.1 3D Printer & Other Equipment

The major pieces of equipment for this experiment include the 3D printer, a multi-syringe syringe pump, and equipment for titration. The cost of these parts, along with costs of necessary consumables, possible vendors, and other notes, can be found in Table 7.1.

Table 7.1: Major components of 3D printed reactor experiment

Component	Source	Cost	Notes
Form1+ 3D Printer	Formlabs	$3299	Includes finishing kit, build platform, resin tank, and 1L of printer resin
Clear Resin (1 L)	Formlabs	$149	Consumable
Resin Tank	Formlabs	$59	Consumable (should be replaced after ~2 L resin used or if switching resin type)
Build Platform	Formlabs	$99	Optional (if high volumes of printing are anticipated)
KD Scientific Multiple Syringe Infusion Pump	Fisher Scientific	$4000	Holds 1 to 10 syringes, flow rates 0.001 μL/hr to 147 mL/min
Syringes, tubing, & adaptors	McMaster-Carr	$35	Pack of ten 50 mL syringes with Luer Lock tip, Luer Lock to 1/8" ID adaptors, and 1/8" tubing
Ring stand and clamp	Fisher Scientific	$140	For securing printed reactor during
Titration set-up	Fisher Scientific	$500	Includes stand, 50-mL buret, buret clamp, and glassware

The printer used in this experiment, shown in Figure 7.1, is a Form1+ stereolithography printer produced by Formlabs (Somerville, MA). The printer uses a UV laser to cure layers of proprietary clear acrylic acid resin to print layers that can be 100, 50, or 25 microns thick. Unlike an extrusion 3D printer, where layers material is deposited on a stage, the laser hardens the resin into layers on the build platform, which is submerged in the resin tank and pulled upwards as the print progresses. This process allows for the formation of solid devices with embedded channels. Furthermore, this printer was selected because the resin has good chemical compatibility with dilute isopropyl acetate, sodium hydroxide, and the products of the saponification reaction selected for this experiment. Over the common experiment time scale, no noticeable weakening or discoloration of the devices occurs.

To print the reactors, students loaded .STL (stereolithography) files generated in SolidWorks into PreForm software, which is a free download from the Formlabs website

(www.formlabs.com). The software was only installed on the administrator account of the computer attached to the printer to prevent the printing of devices not approved by the laboratory instructor. Once the printer has completely loaded a print job, it may be disconnected from the computer.

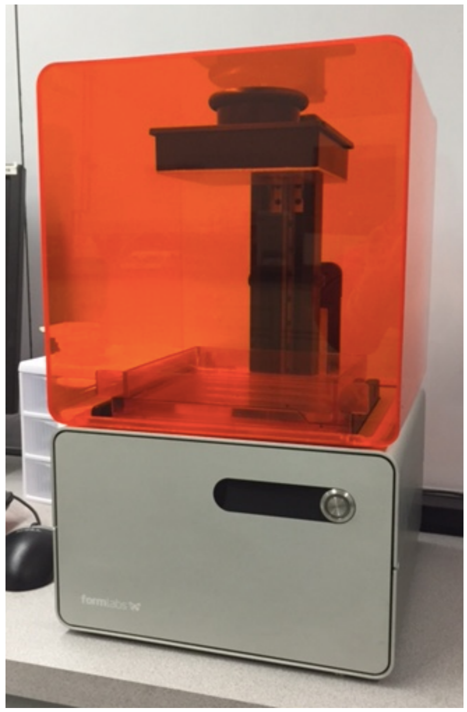


Figure 7.1: The Formlabs Form1+ stereolithography 3D printer used in the UCONN Chemical Engineering Instructional Laboratory

Reagents were delivered to the device using a KD Scientific Multiple Syringe Infusion Pump and 50 mL syringes. With these syringes, the pump was capable of delivering a minimum of 0.001 mL/min of reagents and quench solution, giving students ample range to use varied flow rates. Other necessary materials include 1/8" ID flexible tubing, a 10-mL graduated cylinder for sample collection, a ring stand and clamp to hold the reactor during tests, and a 50-mL buret for titrations.

7.3.2 Chemicals

The isopropyl acetate and sodium hydroxide used in this experiment were purchased from Fisher Scientific. Hydrochloric acid and phenolphthalein are required to quench the reaction and for the titration, respectively. Samples are typically quenched with excess

hydrochloric acid, and sodium hydroxide is used to titrate that excess acid to the phenolphthalein endpoint, which allows for the determination of the moles of sodium hydroxide that had been reacted in the sample.

This experiment is designed to be adaptable to other laboratory curricula, so other chemical reactions may be used. Provided that students can easily quench and quantify the amount of one of the components in the system, any reaction deemed suitable by an instructor is possible. Other acid-base reactions or reactions that produce a colored product or de-color a reagent may also be appropriate for this experiment (Snehalatha *et al.*, 1997, Copper & Koubek, 1998). However, it is critical to assess the chemical resistivity of any resin used when selecting a reaction.

Other chemicals may be required for this experiment depending on the type of printer selected. The Form1+ selected for the experiment set up at UCONN requires isopropyl alcohol during the finishing step. Parts are submerged in the isopropyl alcohol, which dissolves any uncured resin that may still be adhered to the part. The isopropyl alcohol is also flushed through the channels by injection via a wash bottle to remove residual resin inside the device. Other printers, however, do not require a chemical finishing step.

7.4 Methods

7.4.1 SolidWorks Design & Reactor Printing

Students designed their reactors in SolidWorks using tutorial that is provided prior to the start of the first laboratory period (Anastasio & Kadilak, 2015). The tutorial has guidelines and suggestions for designing a device that can be printed with few to no defects. Students were instructed to build their reactor with at least one inlet port for each reagent and at least one outlet port. Students frequently added a fourth port to serve as an inlet for the quenching hydrochloric acid, which is introduced to the reaction stream just prior to the outlet of the device. This port was added to assure that the hydrochloric acid quench was added to the sample at the

same rate as the reagents, simplifying student analysis. A sample device as designed in SolidWorks is shown as Figure 7.2.

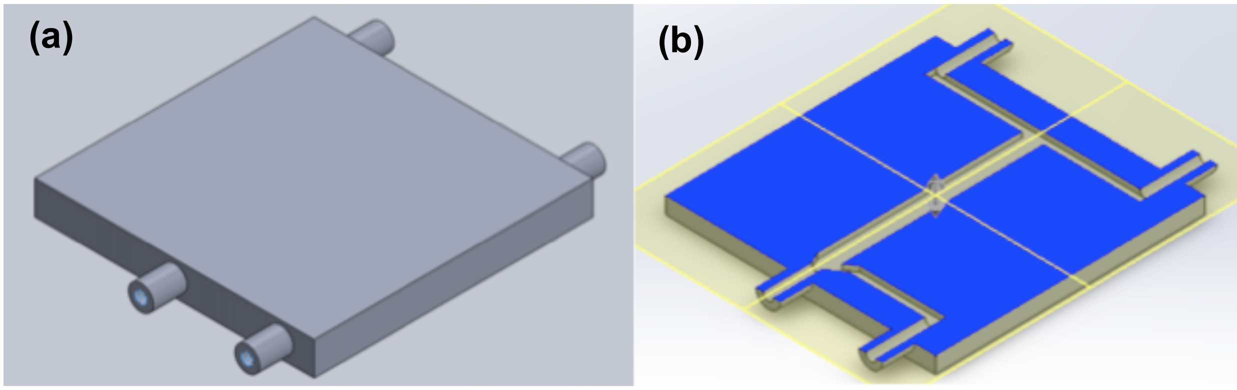


Figure 7.2: A sample laminar flow reactor as designed in SolidWorks, shown from the exterior (a) and in cross-section (b)

Several guidelines should be followed to assure the best-quality print using the Form1+. Each device is a rectangular prism with dimensions 50 mm x 50 mm x 6 mm, and each channel is 2 mm in height situated in the center of the device. Students were instructed to design a channel of any shape within the device as long as all of their channels are no closer than 5 mm to the edge of the device. Students often design simple T-shaped reactors or winding, serpentine channels. When channels wind back and forth across the device, they should not be closer than 2 mm together. These spacing limitations assist laser tracking during printing. It is suggested that each tubing port be cylinders of 3.2 mm in diameter and 6 mm in length. These dimensions make the ports compatible with 1/8" inner diameter flexible tubing. Each port should have a 1 mm diameter hole cut in the center, which should be extruded into the device until it intersects with the embedded channel, as shown in Figure 7.2. Tubing ports should also be parallel to each other and perpendicular to the printer stage; any ports oriented parallel to the printer stage are prone to defects during the printing process that render them incompatible with tubing. If these guidelines are followed and defects are noted, it is recommended to clean the tank to remove no partially cured resin and to clean the mirror with optical-grade compressed air.

Once students verify their designs with an instructor to assure the previously mentioned criteria are met, students email their designs to the instructor in .STL format. The file was then loaded into the FormLabs Preform software and properly oriented such that the ports are not parallel to the stage. If using a Form1+, the printer should be set to print layers that are 0.05 mm (or 50 microns) thick to maximize resolution at a reasonable print time. This setting allowed for devices to be printed in approximately 5 hours. Each device uses approximately 15-25 mL of printer resin, meaning each device will cost between $2.25 and $3.75 if using the Form1+. The print should be finished in accordance with manufacturer specifications. If the printer requires a solvent wash to remove uncured resin from parts, it is recommended to the channels with solvent using a wash bottle and blow the channels dry with compressed air.

7.4.2 COMSOL Modeling

Once students have completed the device design in SolidWorks, they copied the sketch of the channel into a new SolidWorks file. The channel was extruded to the appropriate channel height (2 mm) to give a part that is indicative of the shape of the channel. This part was directly imported into COMSOL as a .STL file for the purposes of modeling the reaction in the device. An example of the importable .STL file and the resultant model generated by COMSOL is presented as Figure 7.3.

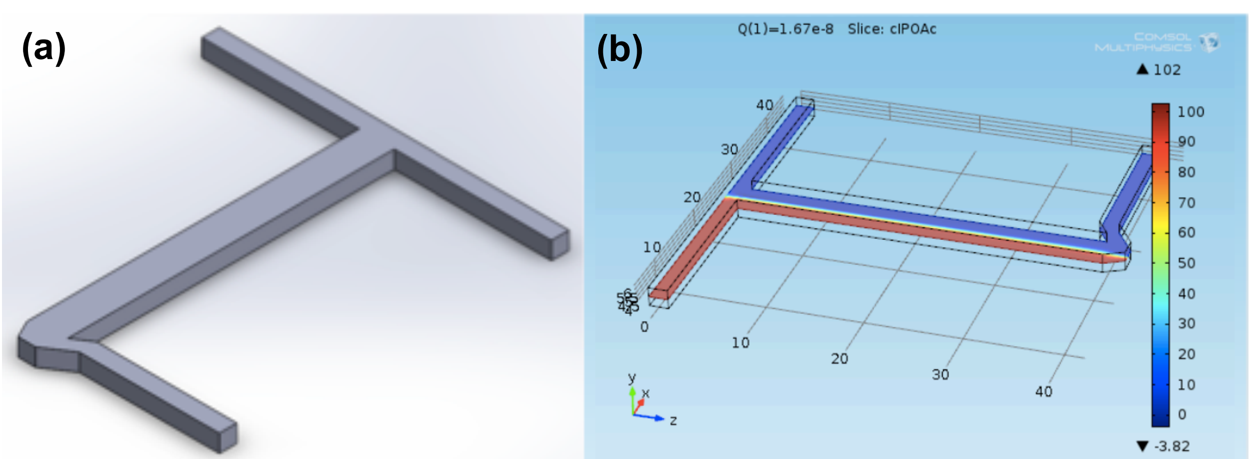


Figure 7.3: SolidWorks image of a reactor channel that is ready to be imported into COMSOL (a) and the resultant completed COMSOL model (b)

Students were not expected to have any prior COMSOL experience before starting this experiment. The students were given a detailed tutorial guide to follow that teaches them how to set up the boundaries of the system, as well as how to define the fluid mechanics, mass transport, and reaction aspects of the model (Anastasio & Kadilak, 2015). The students were given a starting rate constant of 2.1×10^{-5} m^3/(mol s), based on literature values of the reaction rate constant at room temperature (Olsson, 1925). COMSOL also assumed a diffusion coefficient of 10^{-9} m^2/s for each reactant and product, which is relatively close to the actual diffusion coefficient for each material. Students were encouraged to refine the assumption of these coefficients by measuring the laboratory temperature to better estimate the rate constant or by looking up diffusivity values for the reagents and products in literature, but the values provided were an acceptable base reference.

Once students had a working COMSOL model, they were encouraged to use the model to predict how conversion varies with flow rate. This task allowed students to explore reasonable conditions that lead to noticeable conversion of sodium hydroxide, which allowed them to choose flow rates to use in the experimental tests. By manipulating the COMSOL model, students learned which flow rates and residence times were too fast for their experiments.

7.4.3 Reactor Testing

The experimental apparatus for the reactor tests is shown in Figure 7.4. As students were becoming acclimated to the syringe pump, they would frequently inject colored water into the reactor. This additional test allowed students to check the calibration of the syringe pump, visually inspect the device for defects, and take photographs of their device in operation for their laboratory reports.

When ready to test the device with reagent, students loaded 0.1 M sodium hydroxide, 0.1 M isopropyl acetate, and 0.1 M hydrochloric acid into three 50-mL syringes with Luer lock tips. Luer tip to 1/8” barbed tube fittings were affixed to the syringes, and 1/8” tubing was used

to connect syringes and the corresponding ports on the printed device, as indicated in Figure 7.4. The printed reactor was held level and horizontal using a clamp and a ring stand. Students then loaded the syringes into the syringe pump and flowed reagents at a relatively high flow rate (~1-5 mL/min) until all air bubbles were purged from the device. When the channel is completely filled with fluid, the flow rate of the syringe pump is reduced to between 0.02 to 1.0 mL/min (the exact flow rates may be selected based on the results of the COMSOL simulation). Students usually waited one to two residence times for the system to arrive at steady state before beginning to take samples of the reactor outlet in a 10-mL graduated cylinder.

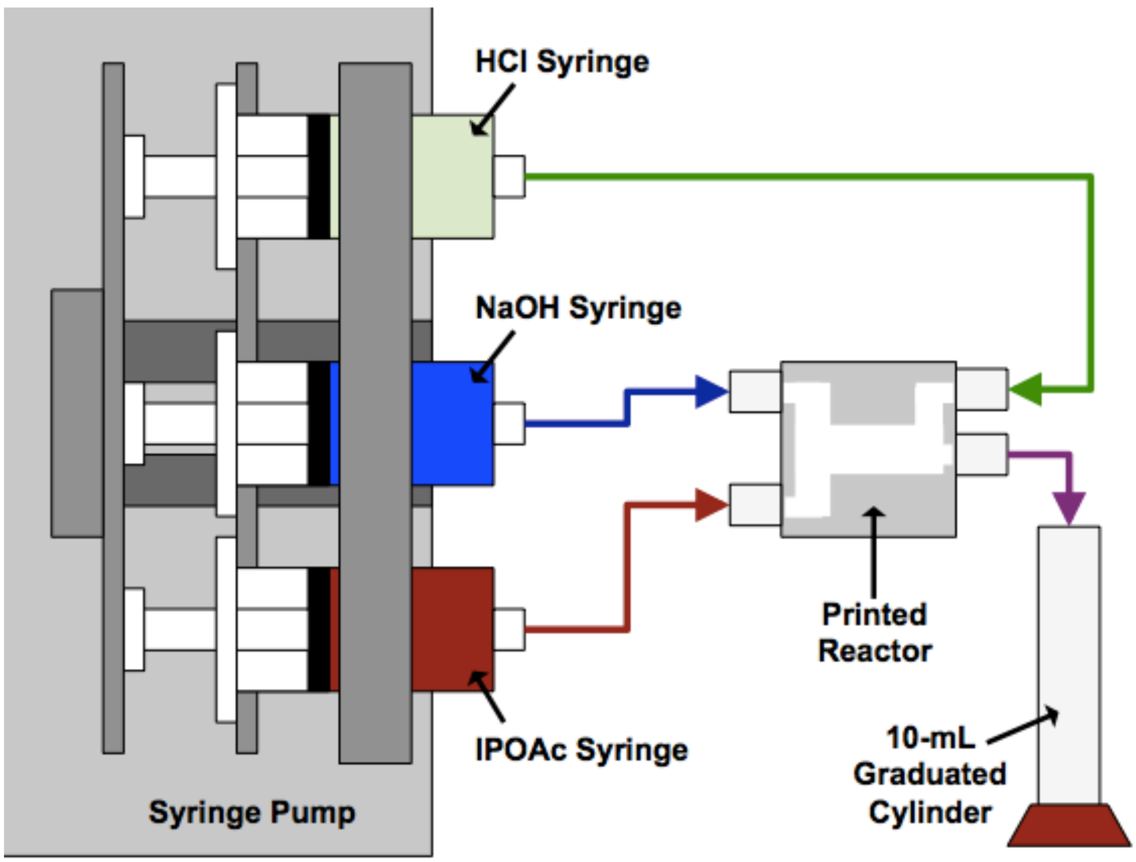


Figure 7.4: Diagram of experimental apparatus for tests of printed reactors.

Once a sample of 3 mL was taken, the sample was titrated to the phenolphthalein endpoint with 0.01 M sodium hydroxide to neutralize any excess hydrochloric acid, allowing students to calculate conversion of reagent sodium hydroxide. The low concentration of the titrant allowed students to perform more accurate titrations at lower conversions of sodium

hydroxide and decreased the likelihood of overshooting the endpoint. It was recommended that three samples should be taken per experimental condition for reproducibility. Students then varied the flow rate within the reactor to examine the impact of residence time on conversion. Alternately, multiple devices were tested while holding residence time constant to examine the impact of channel dimensions and diffusive mixing on conversion.

7.5 Safety Considerations

If performed using the method presented previously, appropriate personal protective equipment, such as gloves and safety glasses, must be worn at all times to minimize exposure to the acid, base, and ester. Mixing and diluting of reagents should be done in a well-ventilated area given the flammability and inhalation risks of working with isopropyl acetate. If using a Form1+ printer, additional safety measures must be taken to avoid exposure to uncured resin, which becomes especially sticky when exposed to light and may cause skin irritation. Gloves and safety glasses should be worn to prevent skin contact with the resin and the isopropyl alcohol bath used in the finishing step. If skin contact is made, the resin should be washed off using only soap and water and not any other solvents. Both the resin and the isopropyl alcohol should be used in a well-ventilated area. Students must also exercise caution when removing their printed reactors from the printing platform, as the spatula used to remove devices is sharp. While the device should come free with a gentle prying motion, students should keep their free hand clear of the top surface of the stage when removing devices to prevent accidental injuries.

7.6 Typical Results & Experiences

This experiment was first run at the University of Connecticut in the Fall 2014 semester as part of the senior-level unit operations laboratory (CHEG 4137W). Students were given six four-hour laboratory periods to design and model at least two reactors. It is possible to perform this experiment in fewer laboratory periods, however, if students are expected to use the laboratory time to perform reactor tests and use SolidWorks and COMSOL outside of class. The experimental documentation specifically asked students to design, model, and test a reactor,

then, redesign the reactor to yield a better conversion than their previous one. Many student groups opted to design more than two reactors. This experiment was performed by three groups of students during the Fall 2014 semester, and, as of writing, two groups of students during the Spring 2015 semester. In total, twelve students have completed the experiment since it was integrated into the laboratory curriculum.

As students design reactors, they are asked to consider variables related to the geometry of the reactor that could enhance conversion of sodium hydroxide. As students are comfortable with sizing CSTRs and PFRs, they typically gravitate toward increasing the residence time, t_{res}, based on the total reactor volume, V, and volumetric flow rate of reagents, Q, shown as equation 7.2:

$$t_{res} = V/Q \qquad (7.2)$$

However, increasing the volume by creating a wider reactor is not an effective strategy to increase conversion in a laminar flow reactor, as more time is required for diffusive mixing of reagents. Thus, equation 7.2 should be rewritten in terms of fluid velocity, U, and channel length, L, shown as equation 7.3:

$$t_{res} = L/U \qquad (7.3)$$

The time required for reagents to diffuse across the width of the channel, t_d, is given by equation 4 (Kirby, 2010):

$$t_d = w^2/D \qquad (7.4)$$

where w is the width of the reactor and D is the molecular diffusivity of the diffusing species. In order to assure that the reactants are fully mixed by the exit of the reactor, students must assume that $t_d < t_{res}$, thus:

$$L \geq Uw^2/D \qquad (7.5)$$

As the Peclet number (Pe) is defined as Uw/D; therefore, to assure that the stream is fully mixed within the reactor volume, the length of the reactor L must be greater than the product of the Peclet number and the reactor width w. Students are asked to consider these

relationships as they redesign their reactors, although some students chose to forgo the channel design for more complex patterns including arrays of circular or hexagonal posts, thinking that these baffles would increase mixing via imposed turbulence.

The expected relationship between conversion and reactor width can be seen in a COMSOL analysis of a pair of T-shaped reactor channels fabricated for this demonstration (but not prepared by students) based on the assumptions given in the tutorial, shown in Figure 7.5. Each reactor shown in Figure 7.5 has a central channel that is 40 mm long; however, the reactor shown as Figure 7.5(a) has a main channel width of 2 mm, while the reactor shown in Figure 7.5(b) has a channel width of 4 mm. The height of each channel was 2 mm. Figure 7.5(a) also demonstrates some alterations that may be required to fully analyze the reactor in COMSOL, as sometimes the additional ports for quenching must be deleted for COMSOL to accurately mesh the device and converge on a solution. The quenching reaction is not modeled in COMSOL for simplicity, so these changes can be made if necessary.

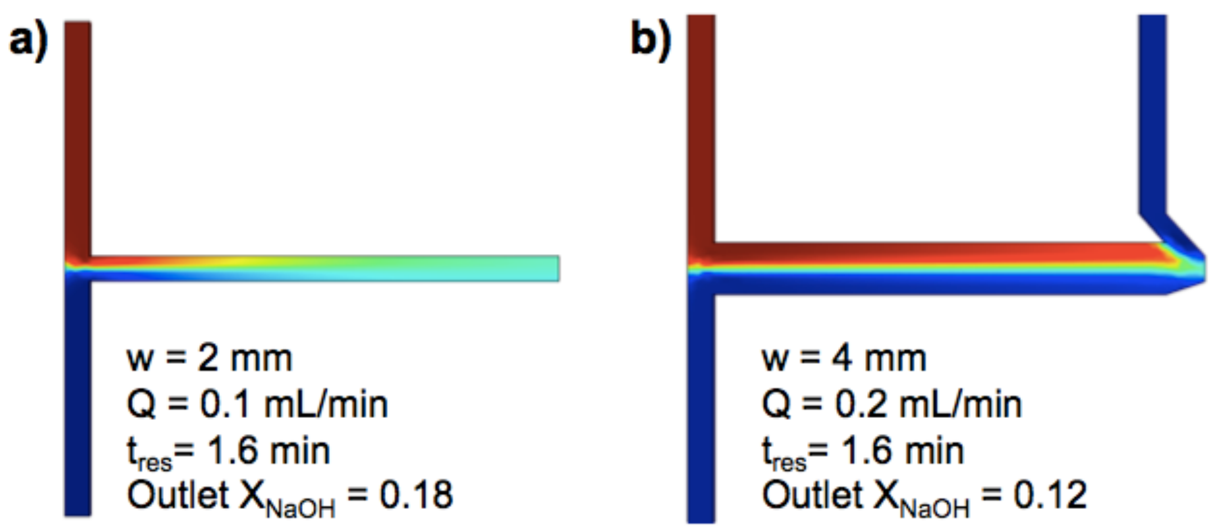


Figure 7.5: COMSOL simulations of sodium hydroxide conversion for a T-shaped laminar flow reactor with widths of 2 mm (a) and 4 mm (b) at constant residence time. The channels are 40 mm long and 2 mm tall. Dark red regions indicate a sodium hydroxide concentration of 0.1 M. Dark blue regions indicate a sodium hydroxide concentration of 0 M. Reaction quenching was not modeled in reactor b.

Figure 7.5 demonstrates clearly that, when residence time is held constant, a narrow reactor will show better mixing of reagents; the wide reactor remains largely unmixed, and therefore, unreacted, throughout its length. Thus, higher conversions are achieved in the narrow reactor. These COMSOL simulations were used to predict conversion in the two reactors at various residence times, summarized in Table 7.2. When normalized for constant residence time, COMSOL predicts that narrower reactors should exhibit higher conversion. While students may not necessarily alter only one geometric variable over the course of their iteration to view this effect, they should expect that conversion should improve not simply by making the reactor longer, but also by making the reactor narrower to decrease the required path of diffusion. This thought process might seem counterintuitive to students who are only thinking that the reactor volume should be maximized to increase residence time, forcing them to reconsider assumptions they are making. Students must also be aware that they may need to alter the fluid velocity as they change reactor width to maintain constant residence time, allowing students to examine a trade-off between reactor conversion and outlet flow rate.

Table 7.2: Impact of channel width on conversion of NaOH as predicted by COMSOL

	Wide T Reactor (w = 4 mm)			**Thin T Reactor (w = 2 mm)**		
Fluid Velocity (m/s)	4×10^{-3}	4×10^{-4}	2×10^{-4}	4×10^{-3}	4×10^{-4}	2×10^{-4}
Fluid Flow Rate (mL/min)	2.0	0.2	0.1	1.0	0.1	0.05
Peclet Number	1670	167	83	833	83	41
Residence Time (min)	0.16	1.6	3.2	0.16	1.6	3.2
COMSOL Conversion of NaOH	0.04	0.12	0.24	0.06	0.18	0.31

Students typically used a less systematic approach when asked to iterate the design of their devices, as the stated goal of the experiment was simply to “redesign the reactor to yield better conversions of sodium hydroxide.” Generally, if students decide to change the width of the channel, they will also alter the channel’s length. As shown in Figure 7.6, students used a

myriad of approaches to improve the reactor. Many students begin by designing the simple T-shaped reactor shown as the leftmost reactor in the top row in Figure 7.6, as the design of this reactor is shown in the provided tutorials for both SolidWorks and COMSOL. When asked to iterate their reactor designs, many students made longer reactors to increase the residence time. Fewer students opted to make narrower reactors. Some students attempted to create channels with rounded corners to prevent fluid from accumulating in the corners 90-degree bends, which students believed would lead to pockets of unreacted reagent. Finally, one group attempted to build channels with static mixers to encourage better mixing, shown as the center and rightmost device in the bottom row in Figure 7.6. In these cases, students found that mixing predominantly only occurred in the center of the reactor, and the sides of each reactor had high concentrations of each individual reagent, leading to poor overall conversion. For the purposes of further discussion, the results from student tests using the simple reactor on the top left (henceforth referred to as the “T reactor”) and the reactor with a long, winding channel (henceforth referred to as the “serpentine reactor”) will be presented. The detailed dimensions for each reactor are summarized in Table 7.3. The serpentine reactor is both half as wide and ten times the length of the base case T reactor.

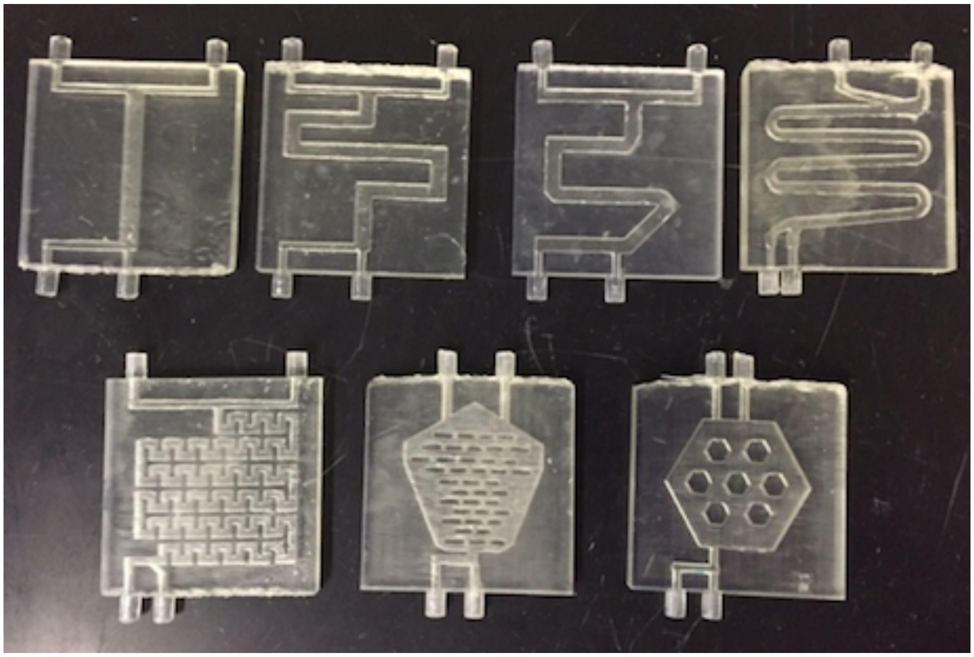


Figure 7.6: Various laminar flow reactors designed and printed by students during this laboratory experiment. The "T reactor" is the leftmost reactor in the top row. The "serpentine reactor" is the leftmost reactor in the bottom row.

Table 7.3: Key dimensions for the T and serpentine reactor channels

Reactor Name	**Reactor Length (mm)**	**Reactor Width (mm)**	**Reactor Height (mm)**	**Reactor Volume (mL)**
T Reactor	40	4	2	0.32
Serpentine Reactor	408	2	2	1.63

When performing tests, students examined total liquid flow rates of 2 mL/min, 0.2 mL/min, and 0.1 mL/min within the main reaction channel. Experimental conversion of sodium hydroxide is shown in Figure 7.7 as a function of residence time for both the T reactor and the serpentine reactor. These results were indicative of what most students saw; as time in the reactor increased, conversion of sodium hydroxide also increased. Moreover, there seems to be a slight elevation in the conversion in the serpentine reactor is slightly higher than the T reactor at lower residence times. This comparison, although not substantially significant due to the large error bars on the 1.6 minute residence time point for the T reactor, could indicate that the serpentine reactor gains better conversion because it is narrower, and thus has a lower

Peclet number than the T reactor. In subsequent experiments, students are being encouraged to evaluate reactors of differing width at the same residence time to make any differences in conversion clearer.

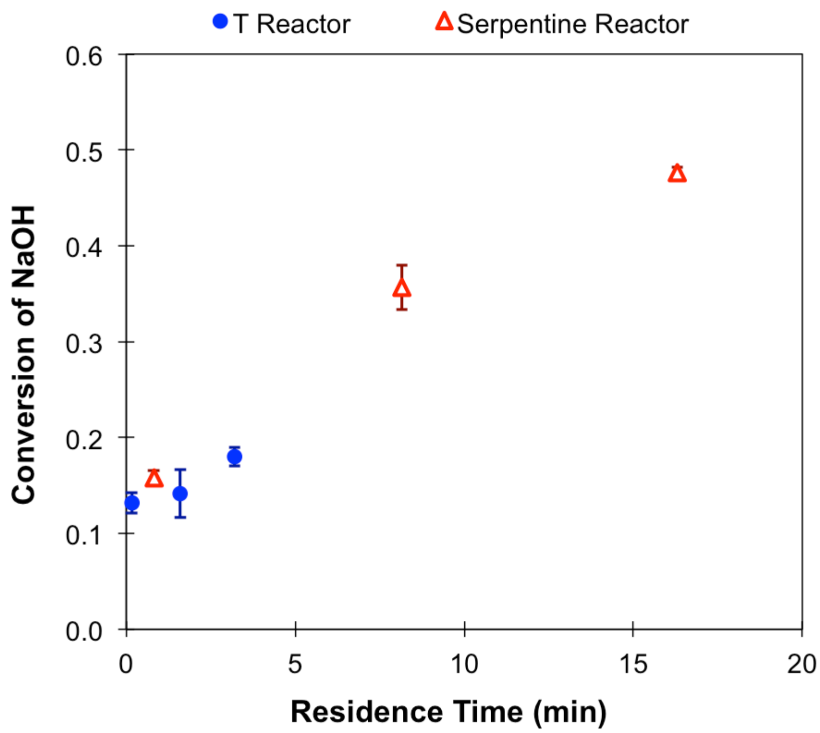


Figure 7.7: Experimental conversion of sodium hydroxide as a function of residence time in the T reactor (circular points) and serpentine reactor (hollow triangular points). Error bars represent standard deviation of three experimental trials.

To assess the accuracy of the experimental results versus the predictions of COMSOL, a parity plot is presented as Figure 7.8, where experimental results are presented on the y-axis and COMSOL predictions are presented on the x-axis. Many of the points fall on the 45-degree line, indicating strong agreement between the experimental results and the COMSOL model, verifying that the use of COMSOL to check the accuracy of the experimental data is valid. Points that diverge from the parity line illustrate two common experimental sources of error. Experimental data points that are above the parity line are likely caused by students inadvertently titrating past the phenolphthalein endpoint. Overshooting the endpoint will cause samples to appear to contain less sodium hydroxide, making conversion appear higher. This

occurrence was more common at lower conversions, when very little sodium hydroxide has reacted and little titrant is needed to reach the endpoint. Further dilution of the titrant may increase the accuracy of titrations. Experimental points that are below the parity line may indicate that students have begun sampling the reactor before the outlet concentration has reached steady state. Students frequently started their reactors at high flow rates and gradually reduced the flow over time. If students did not wait one or two residence times prior to beginning sample collection, they may see lower conversions indicative of the previous flow rate. This problem can be mitigated somewhat by having students wait a full two residence times before sampling.

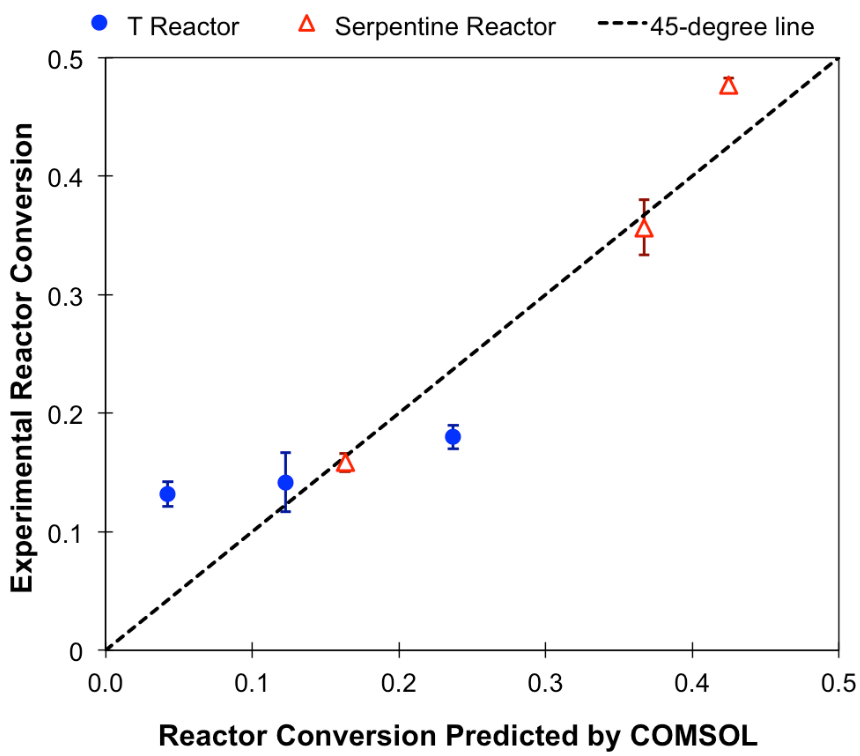


Figure 7.8: Parity plot of experimental conversions of sodium hydroxide versus conversion predicted by COMSOL, setting diffusion coefficients to 10^{-9} m^2/s for all species and rate constant to $2.1x10^{-5}$ $m^3/(mol\ s)$. The dashed line indicates the parity (45-degree) line. Error bars represent standard deviation of three experimental trials.

In general, students have reacted positively to the implementation of this experiment in the laboratory. On experimental exit surveys, students rated the experiment highly in terms of interest in the process and learning in relation to the other experiments in the laboratory

curriculum. Of the seven students who completed the experiment in the Fall 2014 semester, five strongly agreed with the statement "I understand the unit operation or process that pertains to this experiment better than I did prior to the experiment," while the other two students somewhat agreed with the statement. Many students provided anecdotal feedback about the experiment directly to the instructors. Students were very interested in using the 3D printer, as it was a new piece of equipment in the laboratory and due to an increased interest in 3D printing across society. Students also frequently cited working with SolidWorks as a positive experience, as chemical engineering students rarely have an opportunity or reason to learn a CAD software. Some students reacted negatively to the titration element, as they viewed it as repetitive and imprecise, and the COMSOL elements, as they may have neglected a small detail that prevented the model from converging. Overall, students appreciated the overall synthesis of multiple chemical engineering topics into one experiment and felt it was a worthy addition to the capstone-level laboratory. One student went so far as to say this experiment was the best and most useful one she had performed during her undergraduate tenure at UCONN.

7.7 Concluding Remarks

This experiment allowed students to fabricate small laminar flow reactors using a 3D printer. Reactor design was stressed as a key experimental variable by allowing students to design, model, print, test, and iterate their reactors during the course of an undergraduate laboratory experiment. Furthermore, students needed to synthesize topics related to reaction kinetics, mass transport, and fluid mechanics to properly improve on the conversion in their laminar flow reactors, as the fluid flow imposes diffusion limitations to the overall conversion. To assist with the analysis of this complicated system, students compared their experimental results to models created in COMSOL. Typically, student results show good agreement with COMSOL, allowing for some experimental error or model simplifications. This experiment has been received positively by students overall. While some students are discouraged by the titrations, most are excited by the ability to use a 3D printer, and many students comment that

they like how multiple chemical engineering topics are tied together into one experiment. This experiment serves as a good complement to traditional batch and continuous flow reactor (either CSTR or PFR) experiments, as it challenges common student assumptions about reactors. Furthermore, it provides students experience with multiple common software packages, as well as a new manufacturing technique that seems poised to become more commonplace in industrial and academic settings. Moreover, the experiment can be reproduced using other 3D printers and reactions than the ones presented here, making it highly adaptable to the needs of many chemical engineering teaching laboratories.

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SECTION II

IMPLEMENTATION OF GAMIFICATION AND GAME-BASED PEDAGOGIES

"I'd like to be known as the sort of person who saw things from a different point of view from the others."
– Shigeru Miyamoto

CHAPTER 8

GAME-BASED LEARNING BACKGROUND

Sections originally written for:
"Research Review: Engineers at Play: Utilization of Games as Teaching Tools for Undergraduate Engineering Education"
by C. Bodnar, D. Anastasio, J. Enszer, & D. Burkey
for submission to *Journal of Engineering Education* (2015)

As game-based learning and gamification are teaching methods that have been studied and employed for a relatively short period of time, the purpose of this chapter is to introduce the concept of game-based learning before describing the details of the gamification methods used in this work. This chapter provides a detailed definition of a game and explains the benefits that can be had from participating in games, either recreationally or in an educational context. The distinction between games and gamification will be clarified, which will be followed by a brief summary of other studies using game-based learning and gamification in a non-engineering context.

8.1 What is a Game?

Chris Crawford, founder of *The Journal of Game Design*, draws several distinctions between artistic expression, playthings, and what qualifies as a game. The primary distinction between a game and play is that play is unstructured and a game is governed by rules. What separates games from other goal-based acts of creative expression, such as puzzles or competitions, is that competitors are involved who have the ability to influence one another during play (Crawford, 2003). Many others have defined games similarly or added to the definition, mandating that games require player choice, a feedback system to determine how close players are to achieving the goal of the game, or that the systems presented in games must be voluntary (Costikyan, 2002, McGonigal, 2011, Salen and Zimmerman, 2003). Voluntary participation is key; making a game compulsory violates many of the aspects that make it enjoyable.

In recent years since the advent of GBL, a distinction has been drawn between games designed primarily for entertainment and games designed for purposes other than pure entertainment. Zyda draws a clear distinction between a video game and a so-called "serious game." A serious game is defined as "a mental contest, played with a computer in accordance to specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives" (Zyda, 2005). Note that, by this definition, serious games are indeed games and not simulations, as they have a goal and a winning condition. For the purpose of this study, a distinction has been made between games and simulations, as not all simulations can be categorized as games. For a learning tool to be categorized as a game, it must not only simulate a process but also include (1) a goal, (2) rules, (3) entertainment or fun, and (4) a form of a winning condition (Prensky, 2001). Serious games are valuable as they allow the learner to interact with a wide variety of experiences in a safe but realistic environment, granting them experiences that might otherwise be impossible (Hauge *et al.*, 2012).

8.2 Benefits of Games

In recent years, game-based learning (GBL) has come to the forefront of potential pedagogical methods for educating the current generation of students. Games and gameplay operate on the highest part of Maslow's hierarchy of needs, allowing players to meet their cognition needs (to understand, to explore, to experience new things) and their self-actualization needs (creativity, spontaneity, problem solving). Games also provide immediate feedback, letting the participants know that they are making progress and motivating them with rewards to maintain that level of progress. These rewards can vary from the tangible (actual physical prizes) to the intangible (the feeling of victory) (Maslow, 1943). Games also allow simulation of certain scenarios without serious repercussions or penalty if poor choices are made (Hejdenberg, 2005). As such, many aspects common in games (such as a trial-and-error approach to learning and rapid feedback) cater directly to the preferences of current students,

allowing them to become more engaged in the learning process. Engagement is especially imperative to engineering education, as engineering courses have historically been taught primarily via the transmission model, where a fixed body of knowledge is transmitted from instructor to student, often via lectures (Nola & Irzik, 2005). This method is instructor-oriented and enables passive learning by rote memorization, which may fail to garner student investment in the material.

Games serve other benefits aside from addressing student learning needs. In addition to acquiring the appropriate engineering background, employers expect new graduates to be excellent communicators and function well in team environments (Gee, 2003). These skills are not typically brought out in traditional lecture classes; however, these qualities occur naturally in a game environment. Moreover, games encourage experimentation and creative problem solving (Shaffer *et al*., 2005). Often the best solution is not immediately obvious, and trying to discern it can be part of the experience. Games also encourage the formation of strong social bonds and encourage positive, prosocial emotions among players, such as admiration and compassion, while facilitating transformation of groups of strangers into communities (McGonigal, 2011). These social aspects are naturally incorporated into game environments because all players experience triumphs, failures, and choices together. The focus on a common goal causes players to join together, encouraging the players to work together and communicate (McGonigal, 2011).

Compared to a transmission classroom model, a game-based classroom naturally incorporates many ABET student outcomes, such as (d) (the ability to function on multidisciplinary teams), (e) (the ability to formulate and solve problems) and (g) (the ability to communicate effectively). Game-based classrooms can also be extended to promote ABET outcomes (c) (the ability to design a system or component to meet a certain need), (f) (an understanding of ethical responsibility), and (i) (the recognition for the need for life-long learning), depending on the structure of the game (Criteria for Accrediting Engineering

Programs, 2012). However, despite all the perceived benefits of games in educational contexts, many experts in both education and game design agree that more work needs to be done to demonstrate the empirical connection between games and learning (Gee, 2011).

For maximum benefit, games and other interactive experiences must be carefully tailored to the class experience. For optimum student engagement, Barab, Gresnalfi, and Ingram-Goble (2010) posit a theory of transformational play, which states that effective use of games in the classroom incorporates a person (the student) with the intention to make choices, content that stresses relevant academic concepts, and context that can be modified through player choices and that has consequence. In other words, students must be allowed to experience the course content in a way that is personal and important to them. Usually, when games are mentioned in an educational context, computer games, computer simulations, or other forms of 'edutainment' often come to mind. Games in the modern classroom can take multiple forms as necessitated by the nature of the course and material being taught, from in-class games such as educational board games to a game-like structure that forms the backbone of an entire class.

8.3 Definition of Gamification

Game-based learning is not limited to complete games. Gamification is the application of game design elements to non-game scenarios. Deterding *et al.* (2011) state that gamification uses elements of experiences, as opposed to complete play experience (toys) or complete game experiences (serious games). However, the game elements borrowed must impart some rules or structure to the experience; otherwise the experience is playful design. As its design mimics games, gamification promotes the psychological benefits and motivational ability of games in different contexts.

Kapp outlines several game elements that can be effective in a gamified context, illustrated in Figure 8.1 (Kapp, 2012). At a basic level, scores, points, and levels can be implemented to allow players to keep track of their progress, with a rules system to dictate the

distribution of points, allowing for player feedback. Other game elements that are effective in gamified contexts include conflict, competition, cooperation, rewards, story, and replay. These elements can all change with time as the game progresses. Another game element that has been shown to enhance learning is uncertainty, in which the outcome is not known by participants at the beginning and can be influenced by their actions. The addition of an uncertain outcome can motivate participants (i.e. students in an educational context) to spend more time addressing problems and encourage them to have a higher degree of accuracy (Ozcelik *et al.*, 2013).

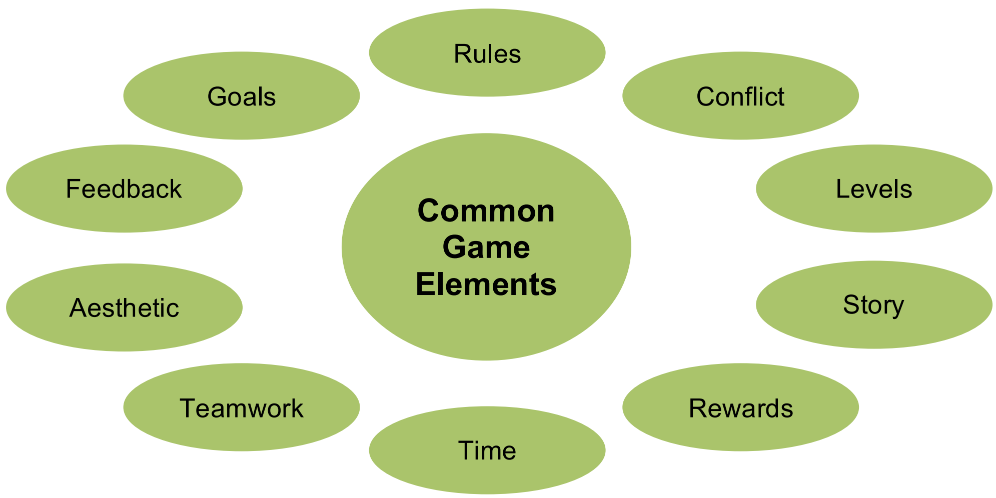

Figure 8.1: Common game elements used in gamified contexts

While there are many ways to apply game elements to a scenario, the most common method is to add scoring, points, or badge system. However, while experience points and digital badges can be effective motivational tools for learners, applying only these aspects of games ignores the truly unique and powerful elements of games such as engagement and storytelling (Kapp, 2012). In order to make gamification meaningful in an educational context, the elements of scoring must be augmented with elements of play. These elements of play can include a compelling story, visualization of learner-created characters, and engrossing activities. Meaningful user-centric gamification has been shown to result in deeper engagement than points systems alone (Nicholson, 2012).

8.4 Games in Education

Examples of effective use of games and gamification in education and training contexts can be observed through trends that are taking place within industry. For instance, large companies have adopted game-like elements into employee training and education. Microsoft implemented an interface that tracked the Windows localization mistakes corrected by their offices around the globe. Employees were motivated to find more mistakes simply by having competition (Language Quality Game – Player Instructions, 2013). Several other companies have integrated games into their employee training, either via team-building games and simulations or by rewarding employees who receive a certain level of training with badges in a company-sponsored social game, motivating employees to receive more training and education (Brousell, 2013).

Many studies have been conducted previously that indicate the efficacy of games as instructional tools. A review by Randel, Morris, Wetzel, and Whitehill (1992) summarized 67 studies of classrooms where games were implemented into lesson plans over a 28-year period. Their findings showed that 56% of the studies showed no difference between conventional instruction and game-based instruction, while 32% found differences favoring game-based instruction. The studies involving STEM areas (math and physics) showed a higher percentage favoring a game-based class (Randel *et al.*, 1992). Hays summarized instructional games for the United States Department of Defense, Navy, and private industry applications. These studies suggest that games can provide effective instruction for a variety of disciplines including math, electronics, and economics, although none of the studies indicate that games are the preferred method of instruction in all situations. Hays also suggests that the instructional games should be implemented in a program that includes a debriefing and feedback, and support should be given to help learners understand how the game improves the overall instructional effectiveness (Hays, 2005). Vogel *et al.* (2006) summarized the findings of 32 game-based courses from the K-12 and collegiate level. Students who participated in games or simulations

showed better attitudes toward learning and showed greater cognitive gains. Ke (2009) showed that 52% of 65 articles summarized showed a positive impact of learning with games. Results of simulation game studies summarized by Stizmann suggest that trainees learned various topics better when the training actively engaged them, such as through games (Stizmann, 2011). While the studies summarized by these authors were not exclusively within engineering education, they suggest that an engaging game-based experience can be a more effective instructional method than the transmission model applied in many collegiate engineering classes.

However, many of the authors of the previously mentioned articles discuss limitations of the papers outlined in their reviews. Some authors conducted a qualitative analysis of learning results. Other authors expressed the need for more quantitative results with respect to student learning outcomes and whether or not the outcomes are achieved more frequently when games are used in the classroom. These two elements could lead to the evaluator's interest having an influence over the data, leading to false positive results. Some of the previous reviews also excluded papers that had insufficient information, including no reported control group or no attempt at a statistical analysis of results.

CHAPTER 9

INITIAL BADGE, POINT, AND LEADERBOARD GAMIFIED STRUCTURE FOR THE CAPSTONE CHEMICAL ENGINEERING LABORATORY

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9.1 Introduction

The capstone chemical engineering laboratory appears to be a somewhat polarizing course. Some students approach the course with numerous preconceptions, such as the course is too much work or that the experiments are dry and bland. Furthermore, in our experience, students typically fail to do simple tasks that can enhance the quality of their lab reports, typically due to running out of time in the preparation of said report. In an attempt to change these trends we notice in our students, many alterations to the laboratory course have been integrated since 2010, including the integration of experiments based on emerging technology and moving to a new laboratory space. However, these elements are costly and not necessarily transmittable to another university. As such, we felt changing the way the course was conducted could be a cost-free way to generate students excitement toward the lab. Therefore, a new game-based structure was devised to apply over the existing laboratory assignments.

The intent of the gamification elements is to increase student interest and engagement in the course, leading to improved attitudes toward the laboratory and increased knowledge retention. Furthermore, the gamification elements were used to incentivize certain actions that we believe would be beneficial to students' future careers, be they in academia or the work force. Hopefully, students would perform the extra tasks and allow them to become habit, contributing to their future success. The game was conducted during the Fall 2012 semester

using a class of 51 seniors. The students were predominantly 20-22 years, and there were 14 female students in the class.

9.1.1 Gamification as an Educational Tool

Over the past several decades, video games have become increasingly mainstream. Today's college students have grown up in an age shaped by gaming. They are not old enough to know a world without in-home game consoles, and the recent surge in popularity of mobile and social games have exposed gaming to the masses. As such, in recent years, educators have been trying to utilize the core mechanics of games to enhance their lessons. This technique is known as gamification, which is the application of game-based mechanics, aesthetics, and thinking to engage and motivate people and promote action and problem solving (Kapp, 2012).

In defining gamification, it is important to define the difference between games and play. Play designates a more free-form experience, whereas a game is a more structured activity with rules[2]. Thus, the distinction between a game and gamification lies in the completeness of the game experience: a game is considered a complete gaming experience, whereas gamification will select appropriate elements of game thinking to utilize. In terms of both games and play, the key action is that the tasks are voluntary; if the tasks are required, it ceases to be playful and is more akin to work (McGonigal, 2011).

Since 2010, there has been extensive research into what exactly constitutes effective gamification of academic courses (Mieure, 2012, Deterding, 2012, Sridharan *et al.*, 2012, O'Donovan, 2012, Nicholson, 2012, Sheldon, 2012). These studies have shown that many common game elements can be effective teaching tools in the classroom. The first common feature is that gamified classes have a clear goal. In some cases this can be as simple as earning a grade in the course. Next, a set of rules is put in place to direct students toward reaching the aforementioned goal. Another common feature of game-based scenarios is naturally occurring cooperative and competitive elements. These elements can be used in the

classroom to allow students to practice these skills. Perhaps students will have to cooperate with other students to accomplish the goal while competing with others. In both cases, students are motivated to achieve the goal.

Games and play can be effective motivators based on people's emotional responses to games. Success in games has been shown to evoke positive emotions that are greater than those in daily life (McGonigal, 2011). Furthermore, many games judge success based on the acquisition of resources. This mentality can be translated to courses. Students can earn a resource as they successfully complete assignments, increasing their grade as the semester progresses. Earning things based on successfully completing assignments, as opposed to losing things based on poor performance, can alter student perceptions of the class and give them a more positive attitude toward learning (Lee, 2012). While it is still difficult to judge if the addition of game elements actually contributes to student learning or retention, and while gamification is not a “magic bullet” that can be applied to every course to equal effect, it can allow students to associate the course material with positive reinforcement (Kapp, 2012, Floyd *et al.*, 2013). Additionally, the novelty of the teaching style can be memorable to students (Miller, 2013).

9.2 Previous Laboratory Organization

In past lab offerings, students would perform three of a possible seven experiments in one semester. Each student performed two experiments that lasted for three lab periods and one experiment that lasted for six lab periods. Partners were assigned at random, and each experimental group functioned independently. In the second semester of lab, students performed three experiments from a different set of seven.

For each experiment, students prepared a pre-lab report that was graded based on understanding of the experimental theory, an experimental plan, and a safety review. Students would prepare a variety of reports for each experiment, including academic-style written reports, business memos, formal PowerPoint presentations, and poster presentations. After their

experiment and report, the students completed an auto-rating form in which they grade the performance of their partners as well as themselves. All three of these components factored into students' final grade in the course. Each experiment received the same weight in the course (i.e. each set of pre-lab, report, and auto-rating are worth 100 points, so each semester is graded out of 300 points). All reports were submitted electronically using the free software Dropbox.

9.3 Gamifying the Base Laboratory Experience

The first step in gamifying the class was the introduction of a new point and level structure. Instead of earning a certain percentage of points on an assignment, students just accumulated total points, called Experience Points (or XP). Assignments and reports were as described above, only now each experiment was worth 1000 XP (for a 3000 XP total). Students began the semester at Level 1, and every 300 XP they earned increased their level by 1. While these levels did not necessarily correlate to letter grades to allow for grade scaling, students were told that a high level at the end of the course would result in a higher final course grade. This method of gamifying a class has been used previously and has been shown to be effective (Lee, 2012). It was thought that this would be effective for the laboratory class, as students would be encouraged by the desire to earn more points, rather than demotivated by the fear of losing points. Furthermore, it was hypothesized that the implementation of levels would motivate students by giving them more periodic acknowledgements of their progress and growth.

In addition to the XP and level structure, another system of points was implemented to allow for rewards that did not have a direct impact on student grades. These points would prevent student extra credit from overwhelming the points earned from required assignments. Therefore, Reputation points (or Rep) were created. It was decided that Reputation would be the win condition of the gamified class in order to give these points weight.

Students were randomly split into six teams, which we dubbed their "Guild." This naming fit the medieval fantasy feel of video games like World of Warcraft and Skyrim that inspired the approach. It was also thought the terminology would resonate with a subset of the students used to gaming terminology. Rep served as a point total for each Guild, and students were encouraged to maximize their team's Rep through completion of the optional tasks discussed in the next section. Some of the tasks could be things that would benefit the students themselves (awarding XP, or points that counted toward their grade), while other tasks would award Rep, and thus help the larger guild as a whole. The team with the highest Rep at the end of the semester would "win the game" and have their choice of a reward based on how well the Guild placed, with the winning Guild voting for which prize they most wanted and the rest selecting among the remaining rewards. For the first run of this system, the three rewards were a pizza party, the ability to pick one experiment to do next semester, or extra XP equal to 10% of your highest lab report grade. It was hypothesized that the natural competitiveness of some of the students would motivate them to complete the extra tasks, and that the students in turn would motivate the other members of their teams to complete the tasks as well.

The terminology used in the game is compared to terminology more commonly used in classes are shown in Table 9.1.

Table 9.1: Summary of Core Game-Specific Terms

Game Term	**Definition**	**Traditional Course Analog**
Experience Points (XP)	Points that contribute to one's overall grade in the course	Grade points
Level	A value that increases as students earn more XP to give a greater sense of progression	Decile; letter grade (if highest level considered an A)
Guild	A group of students randomly assigned a common six-day experiment during the semester	Student team
Reputation (Rep)	Points that guilds amass during the semester; the team with the highest Reputation wins the game	Team points

9.3.1 Choosing and Incentivizing Optional Tasks

With the base level of gamification in place, optional, but beneficial, tasks that added richness to the game structure were included. When contemplating what to incentivize, the following criteria were considered:

1. The extra tasks should not be something traditionally graded, but still benefit students' understanding of the class and good laboratory practice in some way.
2. The extra tasks should not be dependent on skill, ensuring that everyone in the class could participate.
3. The tasks should be optional; a student should be able to complete none of the optional tasks and still be able to pass the course (and earn a high grade). If the tasks feel compulsory, the purpose of the game is defeated.

Using criteria 1 and 2, a list of tasks was generated. These tasks included actions students could take during their experiments (such as presenting evidence of intermediate data analysis), during data analysis (such as looking up examples in textbooks or asking specific questions to the instructors), while writing (such as peer editing or taking their draft to the university Writing Center), and throughout the semester (such as carrying a full experimental design from the first group of the semester to the last).

Criterion 3 was difficult to implement at first. It was undesirable to make all of the optional tasks reward XP, which translated directly into points and, hence, grades. Doing so made the optional tasks feel compulsory, and the extra points might skew the class grades by an unacceptable margin. It was also feared that if students were given ample and readily accessible means of accessing bonus points, then their efforts on the actual assignments, which are the core aspect of the class, might suffer, as they could make up for poor performance on the compulsory aspects of the class with the optional content.

9.3.2 Rewarding Optional Tasks

Students had the ability to earn Reputation for their Guild in several different ways, which have been summarized in Table 9.2 for ease of reference.

Table 9.2: Types of Optional Tasks

Task Type	Description	Possible Completion Frequency	Reward Type	Examples
Quest	Tasks that are designed to encourage quality lab reports	Once per lab report	Rep	Discuss your experimental results with an instructor before your experiment is over
Emblem	Tasks designed to encourage students to work as a Guild	Usually once per semester	Rep	Everyone in the guild is at least Level 8
Achievement	Tasks that reward students for doing more involved or special actions	Once per semester	XP	Complete each of the five available Quests at least once
Title/Ability	Bonuses that reward students for reaching certain levels	Once per semester	XP or Rep	Each Quest you completed is worth 20 extra Rep

Reputation was primarily associated with actions called Quests, which are tasks designed to teach students good laboratory report preparation habits. These tasks were to cite a piece of peer reviewed literature in your report, cite a textbook in your report not included in the laboratory documentation, present evidence of intermediate data analysis during your experiment, talk to an instructor about your data after your experiment was over, and have your written report draft critiqued by the Writing Center. Each of these tasks could be completed once per experiment, but multiple times per semester.

As mentioned above, it was desirable that a few incentivized tasks grant students XP to serve as extra credit (which we called Achievements). Achievements incentivized students to peer review their written lab reports, complete as wide a range of Quests as possible, and present data generated by previous experimental groups to enhance their own. Generally,

Achievements required more effort and long-term planning than Quests did, and they could only be earned once during the duration of the semester.

While the competitive aspect of games was in place, an effort was made to facilitate cooperation and communication between students in the same Guild. This aspect of the game could prepare students for functioning on a large team made up of several smaller teams in the workplace. One way to do this was to incentivize students in the guild to collaborate on their large namesake experiment. As all members of the group would perform that experiment at some point during the semester, they were collectively encouraged to develop a broad experimental plan that could be carried out by the different sub-groups over the course of the semester. The last group would then use all of the accumulated data in their experimental report, and appropriately cite the other groups. Other team-based extra actions, called Guild Emblems, were also introduced. The Emblems were designed to reward students who functioned as a team with Rep. Tasks that earned Emblems ranged from everyone in the Guild reaching a certain Level to making an instructional video for one of the experiments to designing a Guild crest. These tasks required students in the same Guild to work together.

Additionally, taking another cue from role-playing video games, a Title system was added to give more meaning to the Levels. At certain Levels, the students could elect to change their Title, which would grant them and their guild certain benefits. For example, at Level 2, students could elect to become a Lab Squire or a Lab Apprentice. At higher Levels, Squires could select a new Title that could augment the Reputation earned from Quests, while Apprentices could either grant a small amount of XP or a large amount of Rep to their guild. The idea behind Titles was to create a scenario where students would have to interact with one another, strategizing and hopefully trying to balance their group and maximize the amount of Rep they earned in an attempt to win the game. This interaction may also encourage students to think about the class when they ordinarily would not, and also promote the game concept of gaining in power and ability as one progresses through a game. Furthermore, the element of

Title choice was added to give students a sense of agency. Games rely on player choice frequently to help get the player develop a sense of ownership and become invested in the experience. By incorporating a Title choice, it was hoped that students would become more invested in the laboratory experience. For a more detailed explanation of these elements, the authors have prepared a comprehensive rulebook available on request.

The method through which these different point values are combined into a Guild's final Reputation score is shown in Figure 9.1. All XP and Rep earned by students of a Guild are averaged together, and this final number is their current Reputation.

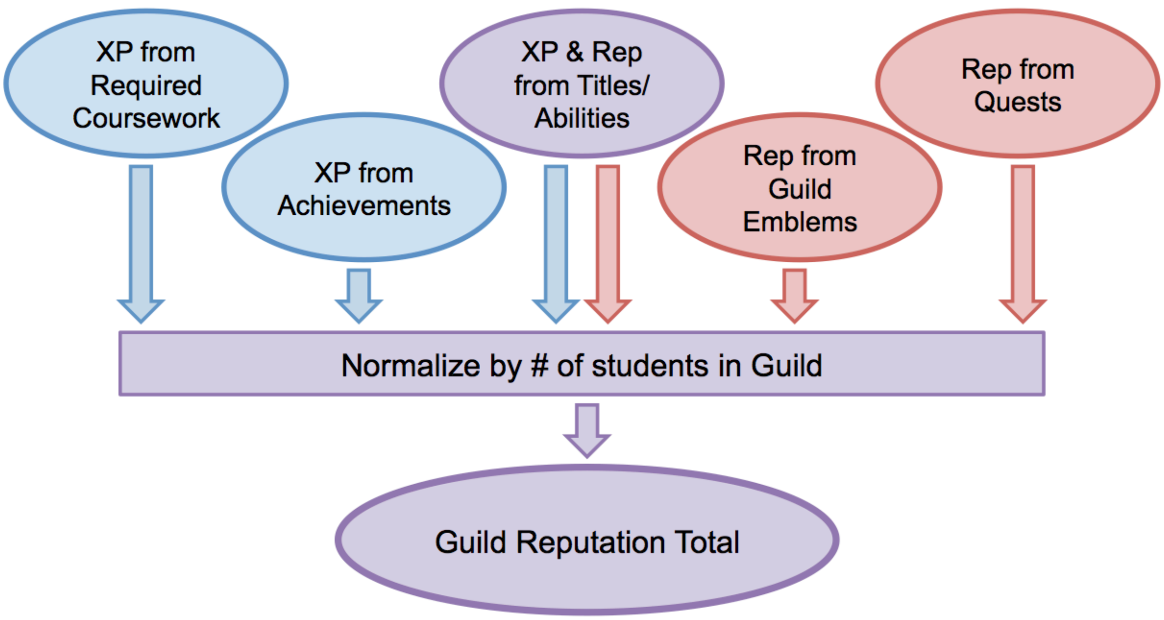

Figure 9.1: Determination of guild Reputation total. Blue tasks reward XP, red tasks reward Reputation, and purple tasks are a combination of both.

9.3.3 Tracking Student Performance

In order to help students keep track of the extra tasks completed, each student was given a report sheet, called a Character Sheet. Character Sheets included grades for all required elements of the course, as well as Quests students have completed and Achievements they have unlocked. At the top of their sheet, students could clearly see their Level, Title, XP earned, and the amount of XP required until they reach the next level. Each sheet was updated

weekly, and students were encouraged to contact the instructors if they noticed any discrepancies. This provided them with weekly tracking of their progress in the class, and because they knew the total number of XP or points available, they could easily see where they were, percentage wise.

A bulletin board in the laboratory was used as a leader board. The board displayed each Guild's current normalized Rep, the distribution of Titles of each student in the Guild, the number of Quests each Guild had completed, and the Emblems each Guild had earned. The leader board was also updated throughout the semester on a weekly basis, and a condensed version was available on the course website.

9.4 Assessment

Student attitudes were assessed via anecdotal evidence and pre- and post-surveys were administered using Survey Monkey. The pre-survey was administered after the game was introduced to students but before the students had begun their first experiment of the semester. This survey was primarily designed to poll students about their attitude towards games in general (including video games, board games, and casual/social games) as well as their initial impressions about the game aspects of the class. After students had conducted all three of their experiments, they were given the post-survey, which asked how students felt about the same game aspects of the class, as well as how much they felt they participated in the game and whether or not we should run the game in the second semester of the laboratory course.

Student participation in the game was monitored by keeping track of the number of optional tasks each student completed in addition to their performance in the class. While a traditional experimental method with a control group was not employed, the content of the course (the style of the required reports, pre-labs, auto-ratings, etc.) is essentially identical to the 2011-2012 academic year. This group of students can be compared to the current group, as the students performed experiments related to the same set of equipment. However, the

students from the 2011-2012 academic year had different graders evaluating their work using similar, but not completely identical, metrics.

9.5 Mid-Year Evaluation

Fifty-one seniors took the gamified laboratory course in the Fall 2012 semester. All students were given the option to participate in the game aspects of the course, and each student did, to varying extents that will be discussed below. Forty-four of the fifty-one students completed the pre-semester survey, and fifty students completed the post-semester survey.

9.5.1 Student Attitudes Toward Games

When asked about their real-life gaming habits, expecting this to be a predictor to their readiness to embrace the game, it became apparent that the male students on average spent much more time playing video games than the female students. However, only three of the female students said they did not play any forms of video games, while the rest had been exposed to the medium via casual or social games. While we were concerned we may be alienating our female students, Figure 9.2 shows that none of the surveyed students indicated that they would not participate in the game at all.

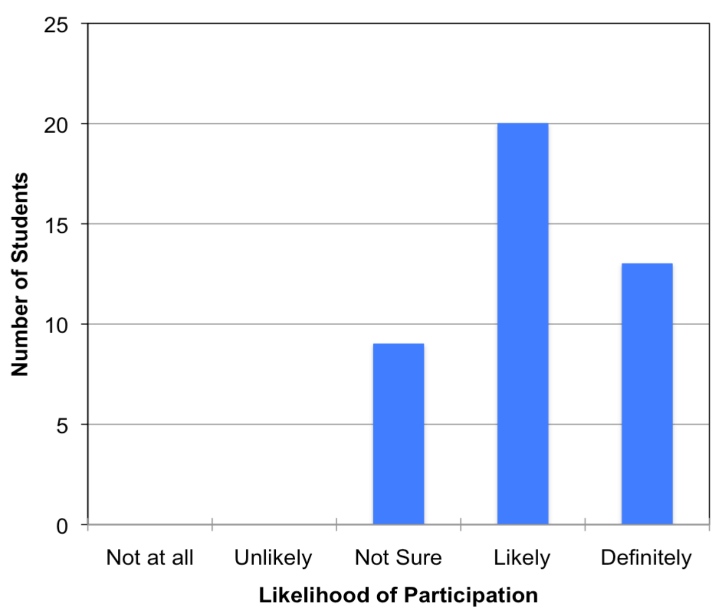

Figure 9.2: Student likelihood of participation in the optional game aspects of the course, based on the pre-experimental survey.

9.5.2 Student Opinion of Incentivized Tasks

Student participation in the optional tasks (the five Quests and the peer editing) can be seen in Figure 9.3, which shows the average number of Quests completed by the students in groupings formed based on their grades on the required course materials, which were the pre-labs, reports, and auto-ratings. While participation in the optional tasks tended to drop with student performance (i.e. high-performing students were the most likely to perform optional tasks), most students participated in at least one optional task per experiment. It is also interesting to note that performance in previous classes does not necessarily predict willingness to participate in the game. Three of the seven students who performed at least 9 optional tasks had a 3.0 or lower grade-point average. This suggested that the game aspects of the course were not just catering to students who would do every task presented to them. Furthermore, the game aspects did not just appeal to the top of the class, as less-high-achieving students were able to join the game and become engaged by the class.

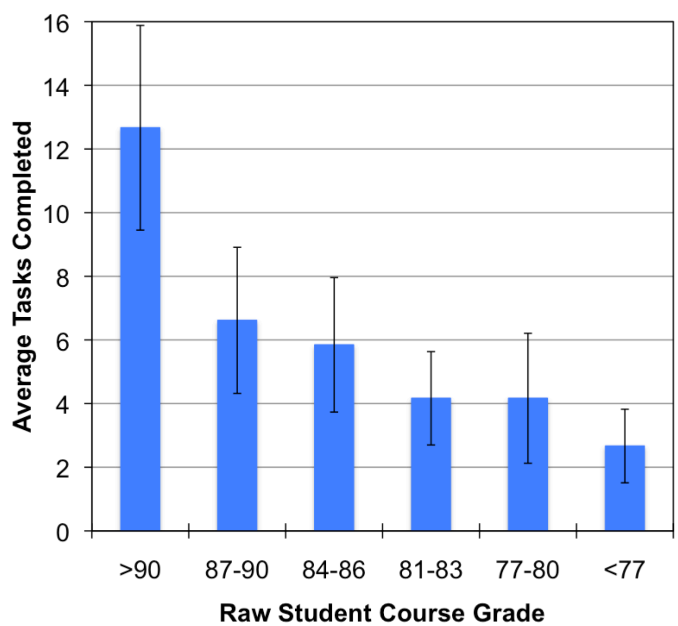

Figure 9.3: Average student participation in optional tasks, sorted by raw course grade. Three students scored above a 90, twelve students scored between 87 and 90, thirteen students scored between 84 and 86, twelve students scored between 81 and 83, six students scored between 77 and 80, and three students scored less than 77.

Participation in the Quests (the optional tasks repeatable once per lab report) decreased as the semester progressed. During the first experiment, students in the class completed 111 Quests. This number decreased to 71 Quests during the second experiment and 52 Quests during the final experiment. This drop-off was slightly anticipated, as students tended to become busier with other courses as the semester progressed. Furthermore, while doing each of the five available Quests was incentivized with XP, continued completion of the Quests after that was not incentivized, potentially contributing to the drop-off in participation. Many students expressed interest in doing the tasks as a means of boosting their grade during the pre-survey; however, they may not have realized the majority of the extra tasks awarded Rep at that time. Additionally, certain tasks, such as having a report critiqued at the Writing Center, were only valid for the written report. This circumstance may have dissuaded some students from pursuing Quests later in the semester if they missed completing ones only available at certain times.

Student participation in each optional task (the five Quests and two Achievements related to peer editing) is displayed in Figure 9.4. Students seemed to favor the tasks that rewarded them for presenting data to instructors during and after their experiment was complete. Students indicated on exit surveys that this task was useful and relatively easy to complete. It is interesting to contrast this attitude with students from last year, as very rarely did they attempt to start data analysis until after their experiment was complete. Therefore, the extra incentive of Reputation appeared to motivate students to perform data analysis early, be able to catch bad data and make up for it in subsequent lab sessions. It is also interesting to note the high participation numbers for peer editing of the written report draft. Like the Writing Center Quest, these Achievements only applied to the single written report of the semester. However, the two peer editing tasks each had greater participation than the external literature tasks, which could be performed for each experiment. This trend is likely caused by students'

ability to earn XP for the peer review tasks, meaning they could boost their grade more directly. Throughout the semester, perhaps unsurprisingly, students seemed to favor tasks that would generate XP.

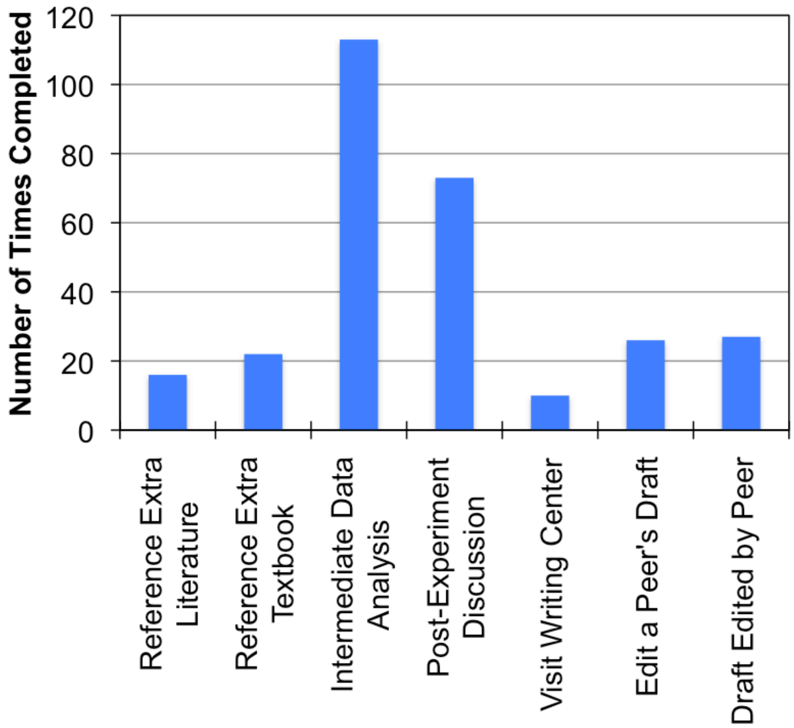

Figure 9.4: Number of times students completed specific optional tasks.

The Fall 2011 semester was used as a point of comparison for this class, as the game was not implemented during that semester. The students' grades on their first written lab reports were compared. Although the precise grading method had changed, in both semesters, students were awarded 30 points for their analysis and 30 points for their communication abilities. In Fall 2011, students scored an average of 45 ± 7 out of the 60 available points. In Fall 2012, with the game implemented, students scored 46 ± 6 of the available 60 points. While the two groups did not show any statistical difference in scores, it should be noted that it is a relatively small sample size (only one offering of each mode of the class was available for comparison), the rubrics used between the classes were not identical, and it can be difficult to control for variations in student performance and preparation in different class years. Moving

forward, it is hoped to be able to improve the quantitative assessment of learning differences, as the lab class will be offered twice per academic year, with different sets of students from the same cohort. This will essentially allow a ‘experimental’ and a ‘control’ group each year. This will be implemented in the fall 2013 semester.

While there is no difference between grades, student attitudes toward the class during the Fall 2012 semester seemed to have improved. Aside from participation in the individual tasks, many students embraced the team aspects of the game. Students in each Guild created Guild Facebook pages where the students could coordinate Title choice and share data for their Guild's major experiment. Numerous students made an effort to wear clothing in their Guild's color during the end-of-semester poster session, which only earned a minimal amount of Rep.

Moreover, the students who experienced the game seemed to have a much more positive attitude towards the course than students in prior years. Previously, some students were very vocal about their frustration with the laboratory course, either disliking experiments they were assigned, worrying that the grading was too harsh, or just writing off the laboratory as something they had to endure until graduation. While this may speak more to the personalities of the current group of students, anecdotally student complaints about the course were lower than expected.

9.5.3 Student Attitudes Toward Gamified Course

At the end of the semester, students were asked to evaluate similar questions to those they took on the pre-semester survey, as well as evaluate how much they felt they participated in the game, how much value they felt they gained from the optional tasks, and whether or not we should run the laboratory as a game next semester. Fifty students out of fifty-one responded to the survey.

According to the survey results, students felt they participated about as much as their classmates and about as much as they expected to in the beginning of the semester. However, students generally felt they participated less than they had anticipated participating at the start

of the semester. Some students indicated that they only wanted to do extra tasks that would help with the preparation of their lab reports and would not go out of their way to complete the others. Others expressed that some of the class was only interested in the tasks that would gain XP. Still other students said they became busier as the semester went on and simply did not have time to complete the amount of extra tasks they had expected to. The students that said they participated more than they expected said they found the extra tasks to be useful in preparing their reports and getting them to think about the experiments.

Next, students were asked to consider the aspects of the game they liked and did not like. Shown in Figure 9.5, students liked the overall idea of adding games to a class, the cooperative elements, the structure of rewards for work, and the incentivized tasks. These opinions mirrored the results of the pre-survey, in which most students indicated they at least somewhat liked the idea of these elements. Many students enjoyed being rewarded for performing actions they felt would strengthen their lab reports. One student noted that she felt motivated to participate in more optional tasks as to not let her Guild down, indicating the cooperative elements in this case can be used well as a motivational tactic. A few students disliked the cooperative nature of the class, citing that it was somewhat frustrating that some of their teammates were not participating in the game, making it difficult for their Guild to win. This situation could be resolved, as one student suggested, by adding smaller XP rewards to more tasks.

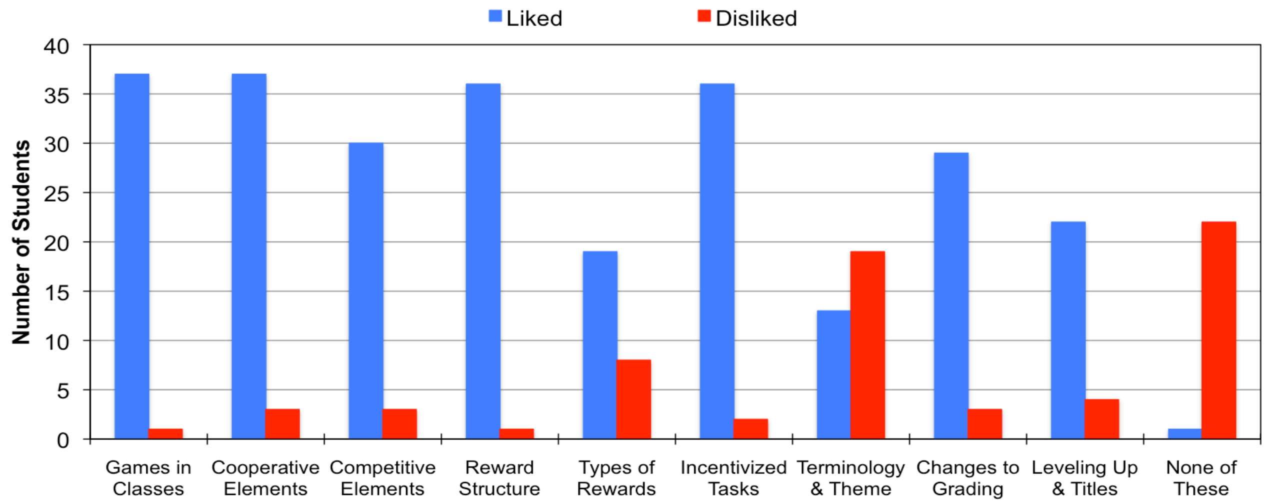

Figure 9.5: Student opinions of various aspects of the gamified course. These opinions were taken during the post-semester survey.

The only elements of the course that more than 10% of the students expressed a direct dislike for were the types of rewards available and the terminology and theme. These aspects also had the least number of students indicate that they liked them. This trend mirrored the results of the pre-survey, in which some students expressed confusion over the terminology and ambivalence toward the theme and rewards. Most students had indicated they slightly liked the rewards in the pre-survey, but most of the students felt neutral towards the theme. Students that disliked the rewards offered (points, pizza, or choice of experiment) felt that either the rewards were too balanced, so placing didn't matter, or that one reward (i.e. the extra XP) was worth much more than the other two. The theme and terminology failed to resonate with many of the students, as the students that indicated they didn't play video games felt somewhat lost. This situation was not the case for all students, as by the end of the first round of experiments many were using game terms correctly in conversation with one another, indicating they had a firm grasp of the game terminology. However, the overall attitude of the class toward that game seemed promising, as almost half of the students indicated they had no significant objections about the game as it was run this semester, citing the game's novelty and the change from a traditionally taught class.

When asked their opinions of the various tasks we incentivized, students felt that intermediate data analysis, discussing data with instructors, and peer editing were useful and valuable. Students on average felt neutral about the usefulness of searching for outside references and going to the writing center. The attitudes towards the writing tasks varied greatly from the seniors from the previous year. In the 2011-2012 academic year, we had required students to peer edit their drafts and had no incentive to get their drafts edited by the Writing Center. These students largely disliked peer editing and found it not very useful, and none of them brought their reports to the Writing Center.

Finally, students were asked their opinion of the game as it was run this semester. Figure 9.6 shows that the majority of the students enjoyed the game aspects of the class and that gender did not dictate student opinions of the game. When asked if the class should be run as a game again next semester, which is possibly the ultimate determination of the success or failure of this endeavor, the students were overwhelmingly positive. Of the 50 students that replied to the survey, 43 gave a definite yes to running the game, 6 students were ambivalent, and 1 student said a definite no. This suggests success in creating something that students found engaging and want to participate in again. In general, students found the game elements "refreshing" and made lab fun when it could have otherwise been seen as dry or boring. One student in particular felt that the game took away a perceived negative stigma attached to engineering laboratory courses. Some students indicated that they felt less anxious and stressed about grades and the class in general, as there were ample opportunities to "make up" for low report grades. Other students felt they had a sense of camaraderie with their Guilds, which they may not have experienced if the game aspect had not been introduced.

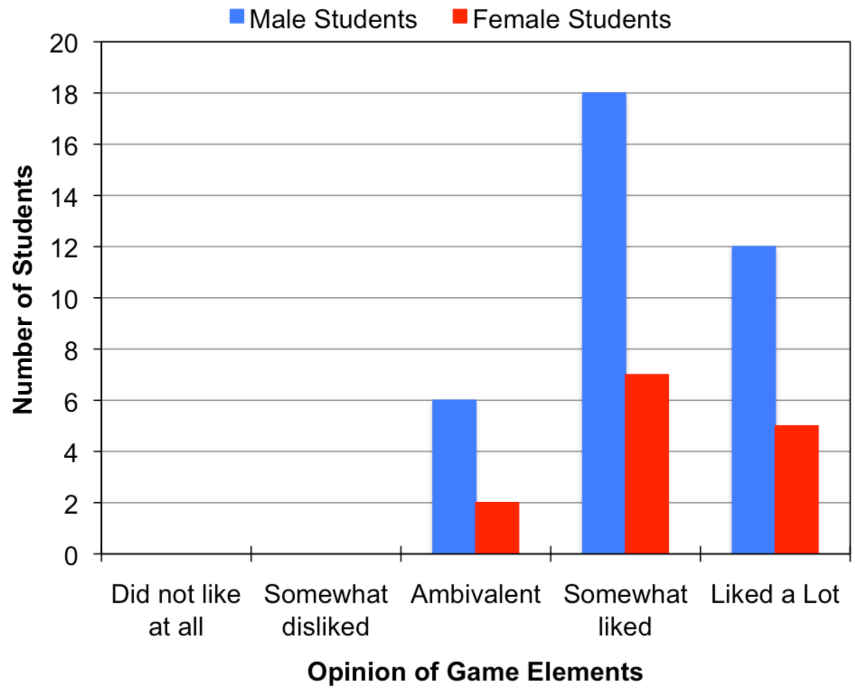

Figure 9.6: Student opinion of overall gamified course, displayed as the responses of male and female students.

9.6 Areas for Improvement

A few areas were noted that could be improved for future offerings. The first major area that a large percentage (greater than 10%) of the students disliked was the use of the medieval fantasy theme and the terminology associated with it. While 28% of the 42 students that took the pre-semester survey indicated that they disliked or were confused by our terminology, 38% of the 50 students that took the post-semester survey indicated they did not like the themes and terminology. Students commented that they either had no attachment to the fantasy theme or were confused by the different terminology (such as the difference between a Quest and an Achievement). As such, at the end of the semester, we had the students vote for a theme for the following semester, with ideas ranging from the current theme to a popular property like Star Wars or Harry Potter to a Clue-style murder mystery. Allowing students to help design the game or have input into the theme of the construct may help broaden engagement and promote

investment in the course. Additionally, students may be able to grasp the game more fully if they're dealing with terms that are familiar to them.

In addition, it was somewhat underestimated how much students valued XP. This trend was apparent when tabulating student votes for their rewards, which was the other major area that needs reevaluation. Of the six Guilds, four of them selected the lab report point boost as their most-desired reward, even eschewing the ability to select an experiment to perform in the spring semester, which the instructors considered as the most valuable reward of the three. The instructors purposely tried to think of rewards that were more original than extra points, and the point boost reward was considered to be a consolation prize for the last-place group. As it turned out, one of the winning groups that selected the point boost did not benefit from them, as six of the eight students already had an A in the course. However, light was shed on this mentality in the post-semester survey, as one student commented the pizza was not viewed as a good prize because it was essentially “saving $6 on a meal” as opposed to something that would benefit them in the class (indeed, the pizza was selected last by all six of the groups). These will be considered when devising rewards for the spring semester, since pizza was unpopular and the selection of an experiment will not be an appropriate prize.

On the same note, while an effort was made to balance the Lab Titles in terms of overall Rep payout, students clearly valued XP more than Reputation. This trend can be seen in the fact that, while there were four different final Lab Title tracks to choose from, 43% of students elected to be Lab Healers, which was the only Title that could boost XP and not just Rep. There was no limit imposed to prevent all students in a Guild from selecting the same Lab Title. The members of Guilds that had fallen into third place early on generally opted to become Lab Healers; many students in these positions felt that they weren't going to win the game, so they may as well try to maximize their XP total. This occurrence would appear to be a variation on the classic Prisoner’s Dilemma from game theory, in which participants will often choose to maximize the benefits to themselves over possibly greater benefits achieved through

cooperation. In the context of the class, this mentality was slightly disappointing, as there were ways for the teams to boost their Rep if they picked more diverse Titles or completed more optional tasks. However, as stated earlier, many students indicated in their post-semester surveys that they would have liked to participate more; they simply did not have the time. To remedy this imbalance, the Title and Ability system was overhauled in the spring semester to try to further the concept of collaboration and cooperation. A limit was placed on the number of students on a team that could hold any given Lab Title.

To address the student complaint that some of the optional tasks (including the peer editing Achievements and the Writing Center Quest) were only valid for the one written report, and because the spring semester is focused more on group reports, these actions will no longer be Quests or Achievements. Instead, they will be replaced with tasks that incentivize students to keep the laboratory neat (which has traditionally been an issue) and to explore the broader impacts of the technology they are experimenting with (which helps fulfill ABET criteria h and i). Rewards for peer editing and visiting the Writing Center will be converted to a Guild Emblem/Team Award if a certain amount of students complete it. It is expected that participation in these activities will decrease, but it is also desirable to leave some incentive there for students that wish to pursue it.

Finally, a tail-off in game participation was observed after the first experiment was completed. This trend was likely due to many students trying to earn the achievement for doing each of the five available Quests in the beginning, then stopping when they either achieved it or realized they could not go to the Writing Center for the final two presentation reports. In addition to restructuring the Quests as previously mentioned, students will unlock Extra Credit points depending on how many Quests they complete. For example, there are 18 possible Quests to complete during the spring semester. Students will earn 10 XP for every three Quests they complete. In this way, students who avoided Quests because they do not reward with XP will be motivated to complete them. In addition, students will be motivated to keep doing Quests

throughout the semester, as the bonus points serve as a buffer in the event of a low assignment grade in the future.

Further improvements for the future include streamlining the method through which students' weekly progress reports are generated. It is time consuming to update fifty-one documents every week. A computer program may need to be developed in the future.

9.7 Concluding Remarks

The game elements of the capstone chemical engineering laboratory course fulfilled most of the goals hoped for. Students became more interested and engaged in the course. Elements of the game that resonated with students the most included the team-based cooperative nature and the ability to earn extra points by performing tasks that, while they had not been traditionally quantified or graded in the past, benefit their understanding of the experiments. Many students stated that while they had fun with the game elements, they understood the value of the additional tasks they had the option to complete, which provided a useful learning experience. While it is difficult to discern if students learned the course material better in the presence of the game, it was clear that the game elements left a positive impression on students while motivating them to seek learning they may not have sought in the game's absence. While there are several improvements to be made that we feel could capture the interest of even more students, particularly the underperforming ones, the improved attitude of students toward the laboratory class was an encouraging sign that the first attempt at gamifying the laboratory was an effective teaching tool.

CHAPTER 10

ENHANCING THE GAMIFIED LABORATORY USING A GAME MECHANIC, NARRATIVE, AND CHARACTER CREATION ELEMENTS

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10.1 Introduction

As modern students have come of age in a time where video games, whether mobile, console, or social, have become ubiquitous, game-based learning (GBL) is gaining increased attention as a tool used in education (Hauge *et al.*, 2012, Hartman & Galati, 2000, Foster *et al.*, 2012, Coller & Scott, 2009, Dahm, 2002). In GBL, games are used as environments and contexts where students can learn via trial-and-error with no permanent consequences (Bogost, 2011, McGonigal, 2011, Hejdenberg, 2005). Note that GBL is not merely free-form activity, but one with rules that guide and dictate the experience, as well as offering a condition in which the game can be "won" (Prensky, 2001, Crawford, 2003).

One method of GBL that has come to the forefront recently is gamification, or the application of game elements to a non-game context (Deterding *et al.*, 2011). The idea behind gamification suggests that if activities can be made to feel more game-like, participants will feel more engaged by them and will be more likely to participate (Sheldon, 2012, Deterding *et al.*, 2011). The game elements also give participants additional ways to engage with a certain activity, either through the aesthetic of the game elements or through new problems to solve. Many of the common elements of games that gamified scenarios use in various capacities include rules, goals, conflict, levels, story, rewards, time, teamwork, feedback, and game aesthetics (Kapp, 2012). The specific game elements used in any given context can vary by application, as gamification is a tool that can be applied to multiple contexts; however, there is no one universal method for effective gamification (Kapp, 2012).

While gamification of engineering courses has been garnering interest lately, the majority of gamified courses documented in open literature focus predominantly on badge, point, and leaderboard (BPL) gamification (Foster *et al.*, 2012, Bartel & Hagel, 2014, Burkey *et al.*, 2013, Santos *et al.*, 2013). In BPL gamification, students are rewarded for their actions by earning points, special badges to commemorate achievements, and progression up a leaderboard (Sheldon, 2012). These implementations predominantly focus on rules (i.e. how to earn points), feedback (i.e. how many points you earned), and goals (i.e. you need to earn this many points). While these rewards can effectively motivate student action by providing a reward and an incentive, they do not completely capitalize on all gamification can offer a classroom, such as narrative, conflict, and the game aesthetic (Kapp, 2012). The game elements used in BPL gamification can be made more meaningful to the game itself, which will provide a deeper engagement than the use of a points system alone (Nicholson, 2012). Rather than simply awarding badges, the badges could grant students some special ability during the game. Rather than awarding points that help students win the game, the points could serve a function in the game itself before a winner is declared at the end of the semester. Furthermore, there is little to keep the student invested in the game over the course of the semester when just BPL methods are used. The novelty of game-based systems may wear off more quickly if these limited elements are used. This trend was observed previously in a BPL game implementation in the capstone laboratory course, as students showed high interest in the game initially, but began to participate less in game activities as the semester progressed.

The intent of this study was to develop a more meaningful game-based system that would motivate students to participate more actively in the capstone chemical engineering laboratory course and improve their attitude toward the course for the full duration of the course. Students could participate in optional tasks in hopes of earning additional grade points at the end of the semester. This system would build off a previously implemented BPL system introduced to the laboratory curriculum with some success in the 2012-2013 academic year by

introducing a game mechanic. This mechanic forced the students to defend their point totals from a game-specific force, designed to promote student participation throughout the semester, rather than primarily in the beginning when the concept is at its most novel. Further offerings of the game were enhanced through narrative elements and by allowing students to create their own in-game avatars. The system was designed to be no cost to implement and highly adaptable based on the needs of the individual instructor.

10.2 Course Structure

The capstone laboratory course is a one-semester (3 credit) course taken in the fall or spring of the senior year. This course follows a one-credit fluid mechanics laboratory in the fall of the junior year and a two-credit transport and kinetics laboratory in the spring of the junior year. The capstone course meets for two, four-hour laboratory periods a week, and students complete three experiments (one that lasts two periods, one that lasts four, and one that lasts six). Each experiment has a different style of report; the first experiment is an individually written, 15-page laboratory report, the second experiment is a group oral presentation, and the final experiment is a group poster presentation. As the capstone laboratory fulfills a university writing requirement, students must submit a draft of their written report and have it reviewed by an instructor before turning in a final report.

In general, the course that used the systems described in the next section was graded out of a possible 3300-3500 grade points, in which 2700 were from the three reports, 300 were from student pre-laboratory reports, and 300 were from peer assessments. A few other assignments, such as graded presentation abstracts and a written report draft completeness score, were added to later offerings of the course.

The game structure originally implemented in this course was a straightforward use of BPL gamification. Students were split into three teams and were given optional tasks to complete. These tasks were designed to encourage students to collect higher quality experimental data and improve their laboratory reports, and the tasks were not activities that

were traditionally graded. Completion of individual tasks awarded student teams with team points, which were independent from grade points. This structure is illustrated in Figure 10.1. At the end of the semester, the team with the highest team point total earned a reward, which was most likely a small boost to grade points.

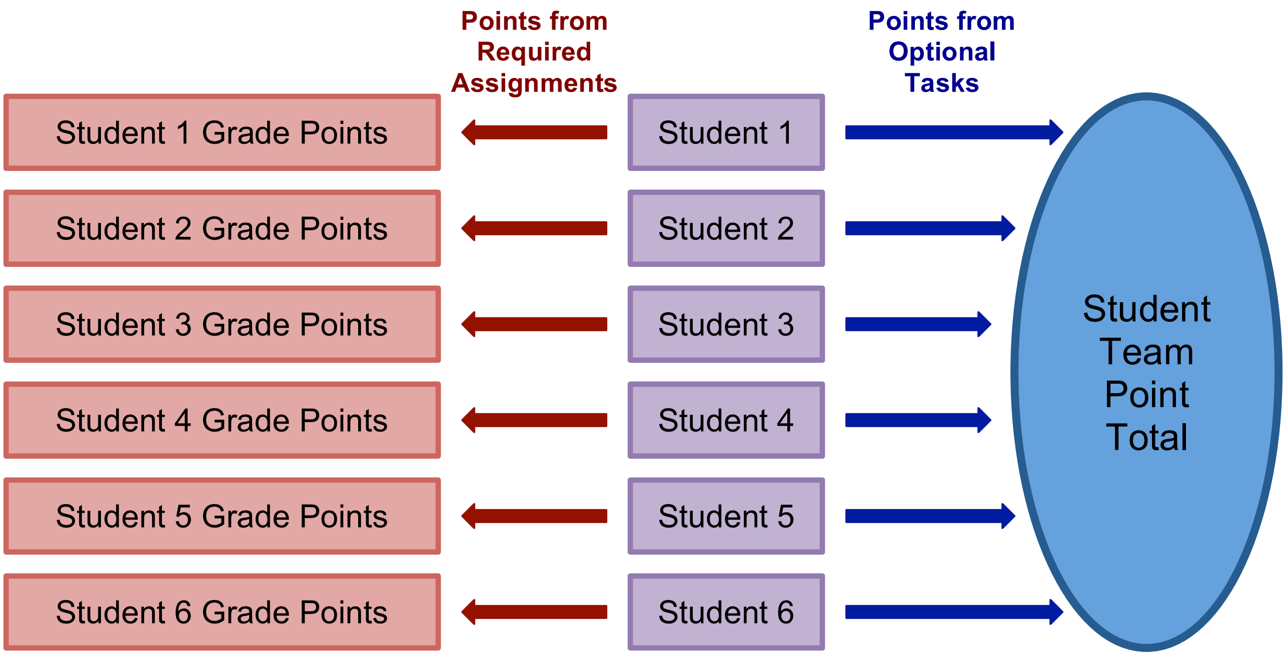

Figure 10.1: Diagram of previously implemented gamified course structure, where students completed required course material for grade points and optional course material for team points.

10.3 New Game Methodology

10.3.1 Game Mechanic

In an attempt to move beyond BPL gamification toward more meaningful gamification, the mechanics of the game were expanded. Rather than simply competing to maximize their team point totals, students collected three different kinds of team points (common points, uncommon points, and rare points), which were earned based on the relative ease or complexity of the tasks. During each experiment period, students collected common, uncommon, and rare points for their respective teams. After each experiment, the defense phase occurs. Student teams have their point totals reduced until a previously announced

amount has been deducted. Teams first lose common points. If more points are needed, they are taken from the team's uncommon point total. If still more points are needed once uncommon points are depleted, student teams will lose rare points. After the defense phase, another collection phase occurs where students are encouraged to continue collecting common, uncommon and rare points. This cycle continues until the end of the semester, shown in Figure 10.2. At the end of the semester, the amount of rare points the student team has maintained will correlate to a bonus amount of grade points added to the grade point totals of each student on the team.

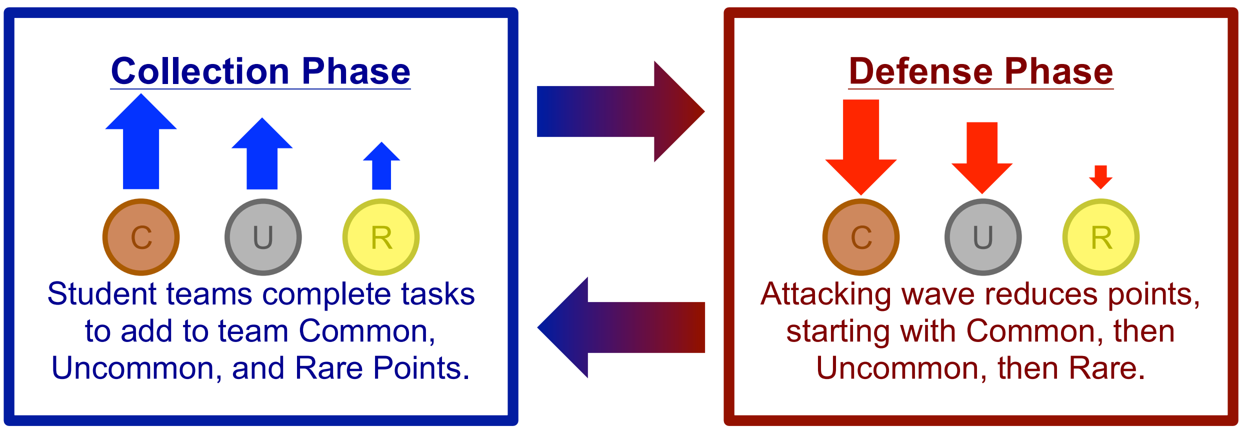

Figure 10.2: Diagram explaining the phases of the game. When implemented into the capstone laboratory course, the cycles repeat three times.

10.3.1.1 Collection Phase

The collection phase occurs while students are performing an experiment. Students are able to complete optional tasks that are designed to encourage them to improve their experimental data and analysis (relating to ABET objective B) and to promote their exploration of the broader impacts of the experiments they are performing (relating to ABET objectives H and I). Completing these tasks would increase a students' team's total of common, uncommon, and/or rare points, depending on the specific task completed. These points allow students to be rewarded for performing these extra tasks, but the rewards are not grade points, which does not diminish the importance of required coursework. A summary of these tasks and the points

awarded is shown in Table 10.1. Note that some tasks award two types of points. This design choice was made thinking that it would discourage students from focusing on a handful of tasks, as there were multiple ways to earn rare points.

Table 10.1: Description of tasks and points that are awarded

Description of Task	Common Points Earned	Uncommon Points Earned	Rare Points Earned
Properly shut down equipment without help prior to experimental check-out	20	0	0
Began experiment data analysis between laboratory periods while experiment was still being done	10	2	0
Discussed data analysis with an instructor after experiment was completed	0	4	0
Cite a textbook not referenced in the experiment documentation in your laboratory report/presentation	10	0	10
Cite a peer-reviewed journal article not referenced in the experiment documentation in your final laboratory report/presentation	0	0	20
Score a 9 out of 10 or higher on the Broader Impacts section of your report	0	2	10

When selecting tasks to incentivize for a class, it is important that the tasks are not related to skills or performance in the class. For instance, there should not be a task that awards common, uncommon, or rare points for getting an A on a laboratory report or for making no mistakes in their experimental analysis. The tasks above were chosen because they are attainable by any member of the class, regardless of skill level, to attract the attention of the middle and lower ends of the class. While it may appear that the final task breaks this rule, students earn a 9 on Broader Impacts by listing multiple impacts beyond the most obvious one (i.e. the ones listed in the experiment documentation), making this a task that anyone can complete provided they have done the research.

The content of the tasks can vary based on the needs or desires of an instructor. Other possible tasks instructors may consider for classes include attendance at office hours or review

sessions, collecting more data than is required for a certain experiment, or for handing in assignments before a deadline.

10.3.1.2 Defense Phase

After each experiment, and also generally after each lab report was graded, the collection phase would end and the defense phase of the game would begin. This phase was inspired by the mechanics of popular tower defense type video games, such as Plants vs. Zombies, Clash of Clans, and Desktop Tower Defense. In these kinds of games, the player is attacked by waves of enemies. The players of these games must erect obstacles to dispatch the attacking waves to protect their home base. In the game-based course structure proposed here, the obstacles are analogous to a team's common and uncommon point totals. The player's home base is analogous to a team's rare point total. Students are told at the beginning of the semester that rare points will correlate to a boost in their final grade, and they must use common and uncommon points to protect these points until the end of the semester. The idea behind this change is that it has the potential to motivate students both extrinsically and intrinsically (Ryan & Deci, 2000). Students are motivated extrinsically by the game's systems; they want to collect points and defend the points they already have because it will result in a higher grade. However, the system can potentially motivate students intrinsically, as the system itself is designed to be more fun, engaging, and variable than the previous model of simply collecting points.

In each defense phase, student teams are "attacked" by a wave of enemies seeking to diminish their rare points. In essence, the attacking waves represent how many points are being deducted from students' point totals, starting with common points, then uncommon points, then finally rare points. If students can pay for the point deduction (or "dispatch all the enemies," in game parlance) using just common or uncommon points, then they will not lose any rare points. The defense phase ends and another collection phase begins, in which

students will attempt to regain common, uncommon, and rare points to withstand the next defense phase.

In order to help students understand the defense phase and how certain points relate to one another, they are given a series of equations that show how many attackers they can ward off with their common and uncommon points, as well as how many rare points they lose if any of the attackers are able to reach that point total. These equations are shown in table 10.2. It is important to note that the three equations are slightly different from one another. For instance, common points may be easier to attain during the collection phase, but uncommon points can dispatch more attackers per point.

Table 10.2: Equations that dictate points lost during Defense Phase

Defense Phase Section	**Governing Equation**	**Variable Definitions**
Part 1: Common Point Losses	$A_1 = A_0 - 0.1[\eta_C(C_i - C_f)]$	A_1 = Attacking force size after Part 1 A_0 = Initial attacking force η_C = Common point efficiency C_i = Initial common point total C_f = Final common point total
Part 2: Uncommon Point Losses	$A_2 = A_1 - \eta_U(U_i - U_f)$	A_2 = Attacking force size after Part 2 A_1 = Attacking force size after Part 1 η_U = Uncommon point efficiency U_i = Initial uncommon point total U_f = Final uncommon point total
Part 3: Rare Point Losses	$R_f = R_i - A_2(11 - K_R)$	R_f = Final rare point total R_i = Initial rare point total A_2 = Attacking force size after Part 2 K_R = Rare point durability (or rare point “efficiency”)

Each of these point efficiencies begins the game at a value of 1. Students are able to manipulate the efficiencies of their team’s common, uncommon, and rare points throughout the semester as they earn grade points, which encourages them to work together as a team to develop a strategy to minimize point losses and allows them to practice critical thinking, collaboration, and communication. As each student reaches certain milestones in grade points, they earn a special ability that can increase one of the three point efficiencies. Early in the class, these abilities may boost an efficiency by 0.5, but later abilities may boost an efficiency by

2. Students selected these abilities via online surveys. To promote diversity in strategy, and to prevent unbalancing the defense phase, each efficiency can reach a maximum of 10. Not only do these abilities allow students to influence the game, but it gives them a sense of ownership and a feeling of progress. Instructors should consider how many grade points an average student has accumulated by the beginning of each defense phase to determine when to award new abilities. If an instructor does not wish to keep track of individual student abilities, he or she can give each team a certain amount of points to distribute in whatever efficiency they wish prior to a defense phase. In either case, the game itself presents a new optimization problem to students, whether they realize it or not. Student teams must develop and execute a strategy to optimize the amount of points they maintain throughout the semester, promoting communication, collaboration, and critical thinking.

An example early attack wave consisted of 140 “enemies” attacking each of the three teams of seven students in the course, or twenty enemies for each student on a team. The class leveling system has been designed so that each student was able to select at least one ability to influence their team’s common, uncommon, and rare point efficiencies. Some teams opted to maximize their common or uncommon point efficiency, which preventing them from losing any rare points in that attacking wave. However, one team opted for abilities that did not increase efficiencies; rather, these abilities would grant them additional points for each optional task they performed during the rest of the class. While this team did lose about 50 of the 100 rare points they had accumulated to that point, the team was able to use the extra point bonuses to recover these points quickly by performing tasks during the second collection phase.

Each attacking wave should be larger than the previous one in order to increase challenge and encourage students to continue completing tasks. Again, it is important to consider how many points students should have earned before each defense phase and balance the size of the attacking wave appropriately. Generally, it can be assumed that 2/3 of the tasks will be completed by students for balancing purposes, although the exact number may

vary. Using the point values and equations shown in Tables 1 and 2, the capstone laboratory course has the first attacking wave be twenty times the size of a student team, the second attacking wave is fifty times the size of a student team, and the final attacking wave is one hundred times the size of a student team. In order to make the game more or less difficult, depending on student participation, narrative elements can be used, as discussed in section 10.3.2. Students are notified of the size of each attacking wave at the beginning of the semester so that teams may plan accordingly.

While this system was designed around a laboratory class with distinct breaking points between experiments, it is possible to adapt the system into other classroom settings as well. In a more lecture-based course, attacking waves may occur following a quiz or an exam, for example.

10.3.1.3 Endgame, Student Rewards, and Grading

After three rounds of collection and defense phases (as the laboratory class has three experiments and laboratory reports), the game ends. Students on a given team earn a certain amount of grade points based on the amount of rare points they were able to keep until the end of the semester. The assignment of grade points can be done directly, meaning the number of rare points can be divided up evenly among team members and converted into grade points. For example, if a student team has 8 students, and that team has 800 rare points at the end of the semester, each student will receive 100 grade points (the equivalent of one extra peer assessment or pre-laboratory report). Later uses of this structure used an alternative reward structure with tiers to dictate how many grade points students earn. This change to the system helps create a greater distinction between rare points and actual grade points, so the link between the two points appears less as a direct one-to-one conversion, while allowing instructors to set a maximum amount of points that could be possibly earned from the game elements. A sample of a tiered structure is shown in Table 4. Using this method, students now have to reach a set milestone to achieve more points, rather than assume that they would earn

one more grade point if a teammate had done one more extra task. Using the numbers shown in Table 10.3, students will earn 100 extra grade points whether they have earned 800 rare points or 900 rare points. As such, student teams are now encouraged to try new strategies as a group; losing a few rare points will not result in a loss of grade points, provided that the team did not lose enough points to shift them into a lower tier.

Table 10.3: Sample rare point to grade point conversion table for a 3400 grade point plass where each student team has 8 members

Final Team Rare Point Total	Grade Points Awarded Per Student on Team
0 – 79	0
80 – 199	10
200 – 399	25
400 – 599	50
600 – 799	75
800 – 999	100
Greater than 1000	125

When implementing a game such as this, it is important to balance the amount of rare points earned as to not overwhelm the core course content. The instructor should calculate how many common, uncommon, and rare points a team of students could earn if they completed all tasks. These values should be checked at each of the major milestones, such as before an attacking wave and at the end of the semester. Doing this calculation can assist with determining the size of an attacking wave as well determining how many grade points students can earn. Using a tiered reward structure can help dictate the overall impact of game participation on a student's grade, as it allows the instructor to put a cap on the maximum possible points students can earn from the game. For instance, if an instructor only wants students to earn a maximum of 50 grade points from this system, the highest tier can be made 50 grade points regardless of the total number of possible rare points, and the rest of the tiers can be scaled down appropriately.

When using this system, it is important to also be cognizant of students who choose not to participate in the game and those who elect to participate to a small degree. This consideration is essential as the game, by definition, cannot be compulsory, as compulsory

tasks can diminish the game aesthetic (Salen & Zimmerman, 2003). To avoid inadvertently lowering the grades of non-participants, grades should first be determined based on the required course materials (i.e. without factoring in any grade points earned from the game elements). Once this grade distribution is determined and the point differentiations between grades is set, the extra game points are added in to determine if that raises the grades of any of the students. Using this method assures that each student will earn at least the grade they deserve based on their coursework, which prevents students who choose not to participate in the game from receiving a lower grade due to others participating highly.

3.2 Game Theme & Narrative

Narrative elements are a key aspect of many popular games. Narrative often promotes an atmosphere of immersion and improves engagement in these games as students begin to interact with and influence the story (Kapp, 2012, Nicholson, 2012). It should be noted, however, that the narrative elements can function independently of the game mechanics described in section 3.1, and it is up to the instructor to decide what, if any, game elements should be used.

The system described in section 10.3.1 is designed to allow any desired theme to be easily applied over it, and anyone attempting to employ such a system is encouraged to use a theme that is interesting to them and their students. The theme will dictate what you call certain elements of the game (i.e. common, uncommon, and rare points, abilities, etc.). Some examples of themes are shown below in Table 10.4. It is highly suggested that the theme for this narrative be a topic that is voted on by the students, as it will ensure that they will be interested in the topic selected. However, instructors should provide options they feel comfortable implementing.

Table 10.4: Sample game themes and thematic names for common game elements (starred themes have been successfully implemented by the authors)

Theme	Attacking Waves are called:	Student Abilities are called:	Common Points are called:	Uncommon Points are called:	Rare Points are called:
Zombie Survival*	Zombies	Equipment	Ammo	Traps	Supplies
Super Heroes*	Villains	Powers	Energy	Stamina	Approval Rating
Fantasy	Fantasy Creatures	Special Skills	Stamina	Magic	Gold
Business	Quarterly Losses	Company Benefits	Discretionary Funds	Reserve Funds	Company Net Worth

While a narrative may help students feel more invested in the game, the narrative does not need to be inherently complex or particularly profound. In order to add narrative elements to this system, a handful of non-player characters (NPCs) were created. Some of these NPCs served as allies to students, giving them additional tasks to earn more points, advance the story, and allowing them to overcome antagonistic NPCs. For instance, when a super hero theme was used, each of the three attacking waves was lead by an NPC super villain. Ally NPCs gave students "secret missions", such as finding a video related to their experiment on YouTube and writing a 1-page essay on how it relates and what they learned, allowing them to look for broader impacts while giving them a chance to practice writing. If half of the students in the class completed the secret mission, the villain NPC would be defeated and the size of his or her attacking wave would be reduced, meaning students would lose less points during the defense phase. These NPC "secret missions" also added spontaneity and uncertainty to the game, which may help motivate students to further participate in the course (Vogel *et al.*, 2006). Finally, these extra missions presented yet another way that students could engage in and explore the potential broader impacts of their experiments.

A narrative also allows instructors an easy way to adjust the difficulty of the game in real time. For example, say students are participating in tasks at a higher rate than expected, and the size of the final attacking wave is too small. The narrative could then be used to justify

increasing the size of the final attacking wave by saying the wave received reinforcements or an NPC has appeared to increase the size of the wave. This justification was successfully used several times during the implementations of the game discussed in later sections; students viewed the changing numbers as simply part of the game.

10.3.3 Character Creation & Progression

A final aspect of many popular games is an aspect of avatar or character creation and customization. These character creation elements can range from selecting specific skills of your player character to controlling their in-game name and appearance. These elements have become popular in social games, role-playing games such as Mass Effect and Dragon Age, simulation games such as The Sims and Minecraft, and Nintendo's Mii avatars. These aspects are popular in games as they better allow the player to identify themselves with the game, which potentially leads to deeper engagement (Adams, 2014). Moreover, studies have shown that watching an avatar that resembles oneself changing in some way can positively impact one's future decisions and actions (Kapp, 2012).

Character customization elements were added to the most recent implementation of this game structure (Fall 2014). As the theme for this game was super heroes, students were instructed to create a name for their heroic identity that would be known only to them. This name was used on the class leaderboard and all public class notifications. Using a selected alternate name allowed for the broadcast of student achievements and selected abilities without violating their confidentiality. While this implementation did not use a visual representation of avatars, it was hoped that students would feel motivated to do well on assignments and participate in tasks in order to unlock new abilities and powers for their hero persona.

Students are also given a personalized PDF that are updated weekly by the instructor. The sheet details their chosen in-game name, the abilities they have selected (referenced in section 10.3.1.2), their grades on required assignments, and what optional tasks they have personally completed. Furthermore, these PDFs have a list optional challenges that students

can complete for minor grade point boosts (usually around 5 grade points per challenge, where there are usually between 10 and 15 challenges per semester). Some of these challenges reward students for meeting individual goals (such as performing a certain number of tasks) or for meeting goals as a team or as a class. Points earned from the challenges are considered extra credit, and they do not factor into the initial phase of grading discussed in section 3.1.3.

10.4 Assessment

This study's primary assessment methods were attitude-based and participation-based. Student attitudes were gauged by pre- and post-semester surveys administered through Survey Monkey. These surveys asked students about their interest in the various game elements. The post-semester survey also asked students to rate their attitudes toward several statements about how the game impacted their attitudes toward laboratory course as a whole on the Likert scale. Students were also asked to evaluate how much they felt they participated in the game and whether or not a system such as this one should continue in future semesters. Both surveys had an optional field for the general comments of students.

Participation in the game elements was assessed by quantifying how many tasks were completed by individual students. Evaluating how many tasks were completed during each collection phase is a strong indicator for student interest in the game as the semester progressed. Additionally, student performance was related to student grades for the individually prepared written report. This report was chosen as the primary indicator of student performance since it is the only grade students do not prepare in a group. The report is typically completed by week six of the semester.

Student attitude and participation data was collected during the Fall 2012, Spring 2013, Fall 2013, Spring 2014, Fall 2014, and Spring 2015 semesters. Detailed attitude and participation data was not collected prior to Fall 2012. The same group of students took the class in Fall 2012 and Spring 2013, as the capstone laboratory class was two semesters at the time, and the junior laboratory courses had not yet been introduced to the curriculum. For the

cohort of students who took the capstone laboratory course in Fall 2014 and Spring 2015, the grades for the students' written laboratory reports were compared to the same students' average written report grades for the transport and kinetics laboratory course, which had no game-based elements, taken in Spring 2014. While the transport and kinetics laboratory reports were not the same length or graded using the same rubrics as the capstone laboratory, they were graded for similar criteria (application of theory, quality graphical elements, appropriateness of conclusions, etc.). Moreover, the transport and kinetics laboratory reports were graded by the same instructor who graded the majority of capstone laboratory reports. This instructor was not responsible for management of the game elements in the capstone laboratory course. While the comparison between these two reports is not perfect, it may help demonstrate what impact, if any, the optional tasks have on student improvement between the junior and senior year.

10.5 Summary of Student Experiences and Discussion

10.5.1 Student Attitudes Toward the Game & Class

In order to assess student attitudes toward the game elements of the course, students were asked to express their opinion on post-semester surveys on the Likert scale, where a 1 indicated "Did not like at all," 2 indicated "Somewhat disliked," 3 indicated "Ambivalent," 4 indicated "Somewhat Liked," and 5 indicated "Liked a lot." The average student response on the Likert scale is shown as Figure 10.3. Cohort A, which consisted of the same 51 students both Fall 2012 and Spring 2013, used the simplified BPL gamification method. The tower defense game mechanic was used for Cohort B, which was comprised of 27 students in Fall 2013 and a different set of 22 students in Spring 2014. The additional narrative and character creation elements were added for Cohort C, where 22 students took the laboratory course in the Fall 2014 semester.

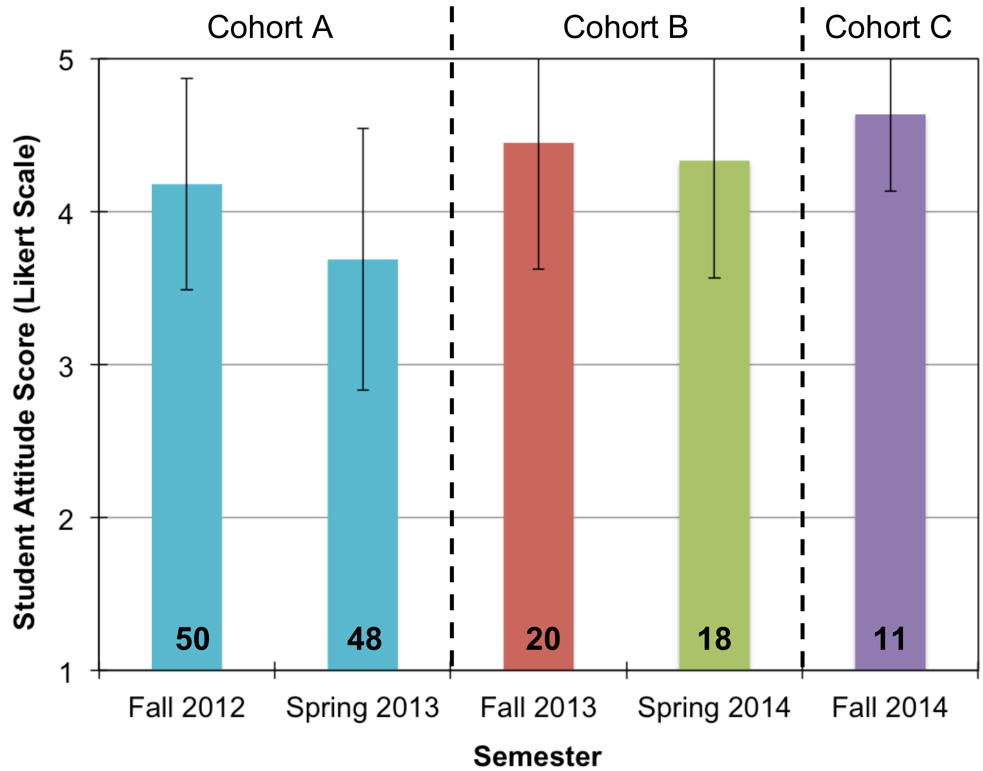

Figure 10.3: Average student opinion of overall gamified course per semester, based on Likert scale where 1 was "did not like at all," 3 was "ambivalent," and 5 was "liked a lot." Fall 2012 and Spring 2013 were the same group of students. The numbers in each bar represent the number of students who completed post-semester surveys. Error bars represent standard deviation.

Figure 10.3 indicates that the inclusion of the game mechanic (prior to Fall 2013) and increased emphasis on narrative and character creation (prior to Fall 2014) yield slight improvement in student attitudes toward the game elements of the course. The graph also illustrates the dangers of overusing game elements in classrooms. Cohort A participated in the game-based laboratory structure for two consecutive semesters (Fall 2012 and Spring 2013). These students felt more neutral to the game elements in the later semester. In post-semester surveys, students expressed that other obligations and classes of the spring semester impeded their ability to participate in the laboratory game. However, it is more likely that the novelty of the game had worn off for these students, as the attitudes of the Spring 2014 students more closely mirrored those of their Fall 2013 counterparts.

Starting in Fall 2013, students were also given post-semester survey questions asking them to consider how the inclusion of the game elements impacted their attitudes toward the

laboratory class. The student responses from Fall 2013 through Fall 2014 to two of these questions are summarized in Figure 10.4 ("The game elements made me think about the laboratory more than I would have otherwise") and Figure 10.5 ("The inclusion of game elements made me feel like the instructors cared about teaching this course").

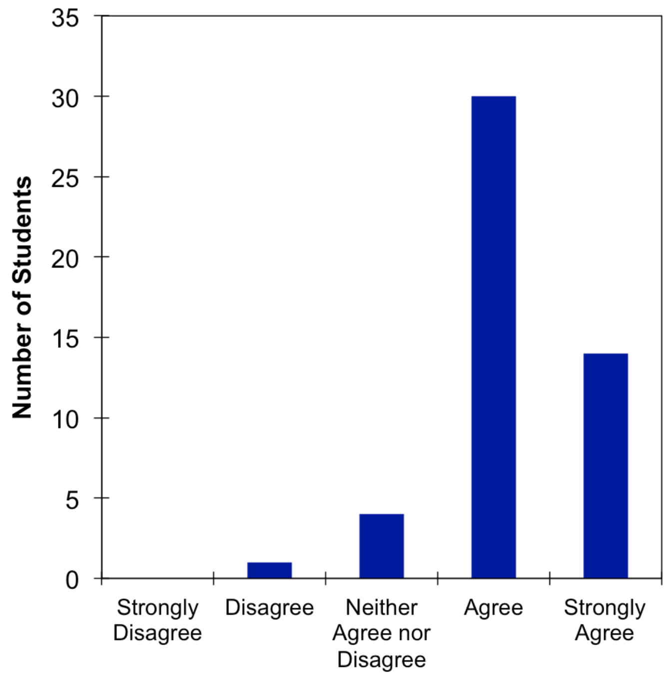

Figure 10.4: Student responses to "The game elements made me think about the laboratory course more than I would have otherwise" on post-semester survey (Likert scale), combined responses from Fall 2013, Spring 2014, and Fall 2014 semesters (n = 49).

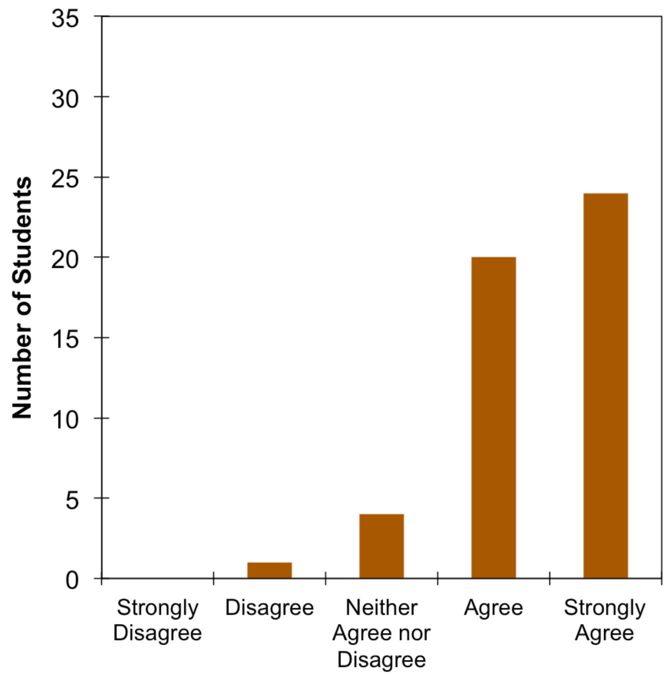

Figure 10.5: Student responses to "The inclusion of game elements made me feel like the instructors cared about teaching this course" on post-semester survey (Likert scale), combined responses from Fall 2013, Spring 2014, and Fall 2014 semesters (n = 49).

These student responses indicate that the game improves student interest in the laboratory course, as the majority of students agree that they thought about the laboratory course more because of the game elements. Forty-four of the forty-nine students polled also agree to some extent that the presence of game elements made them feel like the instructors cared about teaching the course, with over half of those students strongly agreeing with the statement. These attitudes are especially encouraging since it demonstrates that students are more invested in the class and have more positive feelings associated with it. In the long-term, these attitudes may improve student knowledge retention, since the class is now more memorable to the students and they may have an easier time recalling information from it. However, currently a long-term study of the impact of this gamified system on student retention has yet to be completed.

In general, student anecdotal feedback is highly positive. Students who experienced the game with the defense mechanic and narrative focus commented that they enjoyed the game

mechanic and the narrative element, saying that it “took the edge off” the laboratory course while not being distracting to their understanding of the course material. Some students admitted they did not understand all of the systems of the game, but they understood that performing optional tasks would be beneficial to their grade in the long run. Some students did not like that the game was team-based, as they felt that some of their teammates who did not contribute would be negatively impacting the amount of points students who were participating highly would earn. This feedback prompted the inclusion of the tiered grade point reward system discussed in section 10.3.1.3.

10.5.2 Student Participation in Optional Tasks

Student completion of optional tasks, summarized in Table 10.1, was tracked across each semester the game was run. Figure 10.6 shows class task completion for the Fall 2012, Fall 2013, and Fall 2014 semesters. Fall semesters were compared as to eliminate any biases that may occur in the spring semester of a student’s senior year. As the amount of tasks varied between the semesters, task completion is presented as a percentage of possible tasks completed by the entire class. In the Fall 2012 semester (n = 51), the first experiment had six possible tasks (the first five tasks in Table 1 as well as a task to incentivize students to visit the university writing center) and the other experiments had five tasks each. For both the Fall 2013 semester (n = 26) and the Fall 2014 semester (n = 22), each experiment had eight possible tasks, including the six tasks listed in Table 10.1 and two bonus tasks that varied throughout the semester. Students typically only had a limited time (about two weeks) to complete the bonus tasks, which ranged from writing a summary of a news article that related to their experiment to proposing a new experiment that could be performed using the same experimental equipment.

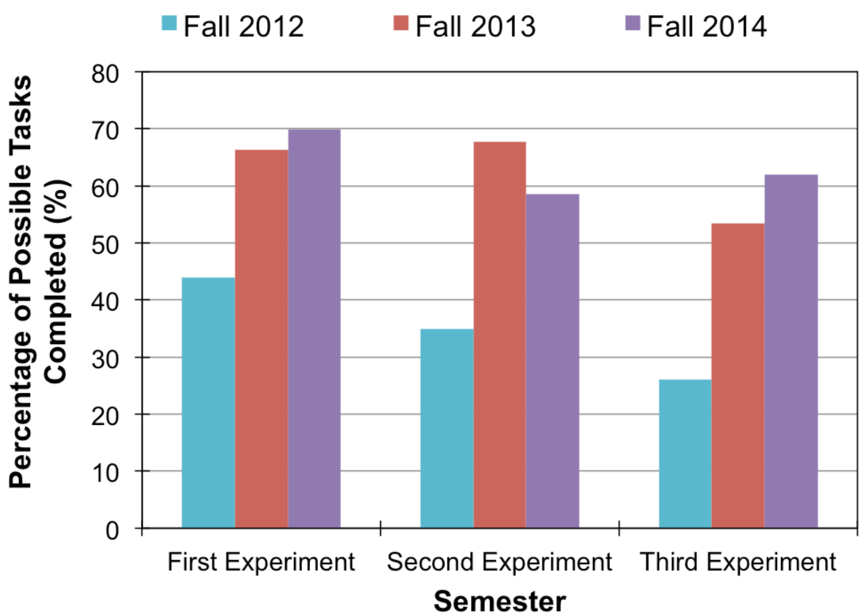

Figure 10.6: Completion percentage of optional tasks as the semester progressed in Fall 2012, Fall 2013, and Fall 2014. The defense mechanic was introduced in Fall 2013, and narrative and character creation elements were introduced in Fall 2014.

Students in Fall 2013 and Fall 2014, who experienced the gamified course with the defense mechanic, showed much higher task completion percentages the students in Fall 2012, who used the BPL gamification method. The lowest task completion percent for a given experiment for Fall 2013 and Fall 2014 (seen during the third experiment in Fall 2013) was still 10 percentage points higher than the highest completion percentage of Fall 2012. This suggests that the game structure highly motivated students to complete more tasks.

Furthermore, Fall 2012 students showed a steady decline in task completion as the semester progressed. While student participation may have fluctuated from experiment-to-experiment in Fall 2013 and Fall 2014, the steady decline seen in Fall 2012 is not present. In this respect, the defense-based game mechanic can be viewed as a success; students were motivated to continue to complete optional tasks throughout the semester, rather than predominantly in the beginning of the semester.

10.5.3 Impact on Student Grades

Evaluation of student learning in the presence of these systems has been somewhat difficult, as the laboratory courses had been restructured during this study. As a result, students did not share all graders between cohorts, and the presence of the junior-level laboratory course meant some cohorts had more experience with technical writing. However, to assess how the game elements impacted student learning between the junior and senior years, the written report grades for the Fall 2014 capstone laboratory students were compared to the same students' grades on their written reports in the Spring 2014 junior laboratory. Any increases may be due to greater laboratory experience as the semesters progress; thus, a comparison between junior and senior laboratory grades may reveal how much student grades improve when students are participating in the game-based capstone laboratory.

To further elucidate a connection between student improvement and the game elements, the students were grouped by the number of tasks they had completed by the time they had turned in their written capstone laboratory report (up to 8 maximum). The average junior lab written report and senior lab written report grades for the students in each group are shown in Figure 10.7.

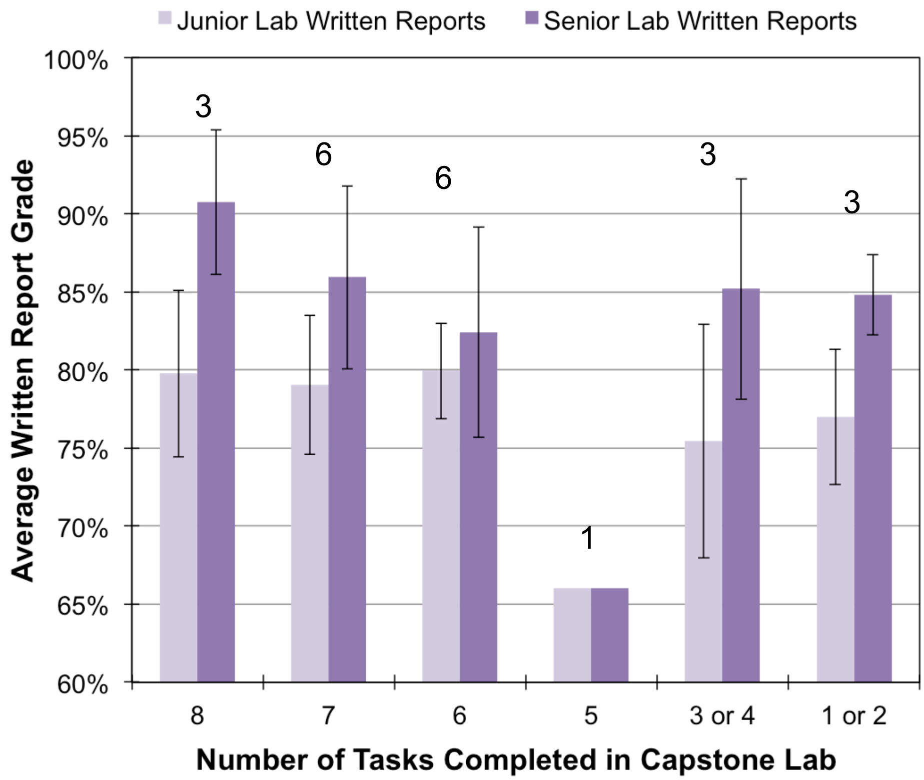

Figure 10.7: Comparison of grades between junior and capstone lab. Students have been broken up into groups based on the amount of optional tasks they had completed in capstone laboratory prior to the first written report submission (up to 8). The number above each column represents the number of students in each group. Error bars represent standard deviation.

Although the small sample size leads to large standard deviation error bars, Figure 10.7 shows a trend can be seen in the students who completed six, seven, or eight tasks. These students generally performed similarly in the junior-level laboratory. However, the students who completed eight tasks showed more improvement between their junior lab performance and their capstone written report. The amount of improvement above the junior level reports decreases with the amount of tasks until students complete less than five tasks. These students show improvement roughly similar to the students who completed seven tasks. Again, the limitations of the small data set make distinguishing trends, if there are any, difficult, and more data will be collected as the game is run in the Spring 2015 semester with a group of students new to capstone laboratory from the same cohort.

It is also notable that, of the sixteen students who completed over 50% of the eight optional tasks available before the completion of the first laboratory report, all nine of the female students in the class are represented. This fact seems surprising, as many assume games are a hobby for young males and additionally assume that game-based learning must be alienating to female students. However, according to a study conducted by the Entertainment Software Association, 48% of all game players are female. Moreover, women over the age of 18 make up a larger percentage of people who play games (36%) than boys under 18 (17%) ("2014 Sales, Demographic, & Usage Data", 2015). As such, one should not shy away from game-based learning for fear of alienating a demographic; it is essential to make the game experience itself interesting and engaging to encourage students to participate.

10.6 Concluding Remarks

The game-based system described in this paper has been shown to be incredibly popular with senior-level chemical engineering students in the capstone laboratory course. The game mechanic based on popular tower defense games serves multiple purposes. First, it provides a unique classroom environment that students feel positively about. Second, it gives students multiple ways to engage in the classroom and contribute while promoting their critical thinking and collaboration skills. Finally, it encourages consistent student participation throughout the semester. In the authors' experience, this system has proven to be much more popular with students and more successful at promoting student involvement in class than a similar gamified course structure that relies only on badges, points, and leaderboards. The use of narrative elements and character creation may enhance the experience further, making students feel like they are part of a unique system that their personal actions can influence. As stated previously, however, this system is designed to be modifiable and customizable, and elements can be taken in whole or in parts to suit an instructor's needs.

The next stage of implementation of this structure involves the development of computer software to track student progress and to keep students informed as to what tasks they have

completed. Currently, these parameters are tracked using Microsoft Excel and Microsoft Word. It can be cumbersome for an instructor to manually input completed tasks, and sometimes mistakes can be made and tasks can be missed. Learning management systems like Blackboard often have tools to allow student groups, optional assignments, and non-grade point awards. However, a customized software or smartphone app that allows students to log-in, customize a virtual avatar, submit tasks, and check their in-game status would be a desirable alternative. Other future work includes a more thorough study of the impact of the game and the optional tasks on student performance, both in terms of performance in the class and in terms of improvement of laboratory skills. It would also be interesting to examine how student attitudes toward the course and the game elements were linked to their overall performance in the course, but the anonymous nature of the attitude surveys make it difficult to draw any direct conclusions. This problem could be remedied by assigning each student a random number and having an external assessor complete the analysis of the data based on students' numbers rather than their names. In the future, a third party assessor may also need to conduct exit interviews with students to assess this connection.

CHAPTER 11

USE OF GAME ELEMENTS IN A PROJECT-BASED FIRST-YEAR ENGINEERING COURSE

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11.1 Introduction

Many institutions have introduced students to engineering design principles in the first year of college education in the form of project-based classes (Sheppard & Jenison, 1997, Dally & Zhang, 1991, Frank *et al.*, 2003). The emphasis on design projects in the first year of undergraduate study promotes active learning via hands-on activities and student intellectual development (Marra *et al.*, 2000). Group-based project work helps students naturally practice what are commonly referred to as 21st-century skills, or skills that students will use to be successful in the modern work environment regardless of chosen career path. These skills include critical thinking, communication, creativity, and collaboration (Trilling & Fadel, 2009). An emphasis on design early in the curriculum is beneficial to students, as many programs only begin to stress elements of engineering design methodology in the final year of instruction.

The critical skills that students can build by engaging in design-based courses can be practiced using game-based learning (GBL) and simulations as well. In game-based learning, games are used to help convey information to students in an engaging way (Hejdenberg, 2005). Games also allow students to experiment with different outcomes in a safe, low-consequence environment, encouraging learning via trial-and-error (McGonigal, 2011, Bogost, 2011). A game is fundamentally different from a simulation, however, as simulations provide unique environments for experimentation, and games have goals and rules. Generally, it is not possible to win a simulation, but once certain goals are met, games can be won (Prensky, 2001). To effectively navigate a game or simulation, one must be able to think critically about

the constraints of the game, collaborate and communicate with others, and devise a creative strategy to win, again promoting 21st century skills (Sheldon, 2012, Kapp, 2012).

As both simulations and design courses can allow students to practice critical skills, simulation and game elements can be used effectively in a freshman design course to augment an already existing project-based structure. As many design projects often have a corporate sponsorship or client angle, a business simulation game can be created. Students are encouraged to form “companies” and create products for specific clients, then compete with other “companies” over which device best fits the needs of the client. Success in the business simulation will come down to students’ ability to work with others, think critically to arrive at creative solutions, and communicate these solutions effectively, reinforcing elements that are presented through the project-based nature of the course.

This chapter will provide a preliminary report of the first implementation of a design-based freshman engineering fundamentals course at the authors’ institution. As project-based courses are not a new development, the authors will predominantly focus on the business simulation and game-based systems that were created specifically for this course. These systems include a narrative framework for the projects, specific rules for students to follow, and criteria for evaluating student projects in the context of the business simulation. These systems enabled student design competitions that were not tied to student grades, so students do not need to worry about performing poorly in the class if their projects do not work. Furthermore, the simulation allows students to practice budgeting and making financial decisions in a safe, low-consequence context as they use a fictional currency to buy materials for projects. Preliminary student experiences in the class will be expressed primarily as student attitudes toward the course and the additional elements compared to courses they have taken in the first semester of their freshman year. Students rated how comfortable they felt with working in groups and communication skills before and after the semester. While the data is preliminary, initial trends in student attitudes are useful at this stage of course development. The paper will

conclude with alterations that are currently being enacted upon in the current semester offering of the course (Spring 2015).

11.2 Course Structure

The Foundations of Engineering course is offered only in the spring semester of the freshman year. While the course is a general engineering class, each separate engineering department teaches one section of the course. The purpose of the course is to provide freshmen with general engineering skills that can be applied to any engineering discipline through the context of the selected discipline. The section of the course used in this study was the chemical engineering section.

Over the course of the class, students completed three projects. The first was to design a thermos capable of keeping a vial of water cold when submerged in a hot water bath. The second project involved the design of a water filter to remove clay particulates and food coloring from a simulated contaminated water source. The third was a variation of the American Institute of Chemical Engineers (AIChE) Chem-E-Car competition, where students used a reaction of baking soda and vinegar to propel small cars to a target. Students completed these projects in groups of 3 or 4, preparing short written deliverables as a group throughout the course of the project before delivering a final oral presentation about their completed device. Students also completed individual weekly quizzes and two exams (a midterm and a final) on course material in order to grant students more individual control over their final grades. The full breakdown of student grades is shown in Table 11.1, and course grades were made up of 60% group work (20% for each project) and 40% individual work (quizzes, exams, and peer assessments).

Table 11.1: Assignments as contributors to student grades for the Spring 2014 semester

Item	Points per Item	Number of Items	Total Points (percent of grade)	Notes
Proposals	50	3	150 (15%)	Team grade
Progress reports	50	3	150 (15%)	Team grade
Presentations	100	3	300 (30%)	Team grade
Peer Assessment	30	3	90 (9%)	Individual grade
Midterm	1	100	100 (10%)	Individual grade
Final Exam	1	100	100 (10%)	Individual grade
Quizzes	10	10	100 (10%)	Individual grade
Final Assessment	10	1	10 (1%)	Completion based

The class was first run in this manner during the Spring 2014 semester. The class met once a week for a 2.5-hour period, where approximately one hour was devoted to lecture and 1.5 hours devoted to design time. Optional two-hour design periods (labeled as office hours) were offered three times a week if students needed more time to design and test. The course had 65 students, one primary instructor, and four teaching assistants. The operating budget for the materials, storage, and tools needed for the design projects was $4000 for the semester.

11.3 Simulation & Game Elements

11.3.1 Management Simulation Elements

The management simulation elements frame the course as students forming companies to build specific devices for a client. The specific needs of each client change depending on the project to add variety to each project. For instance, students needed to design a lightweight thermos. In the filter project, weight was not an issue for the client, but ease-of-use was. The clients were used to show students that the most important factors of a design will vary from project-to-project.

Students were also given budgetary constraints in the form of a fictional currency developed for the course. These elements were intended to promote proper planning and allow students to balance device efficacy and cost.

11.3.1.1 Company Group Structure

In order to add more business management element, student teams were labeled as "companies." Each company had a chief executive officer (CEO), a chief financial officer (CFO), and a chief technology officer (CTO). Groups of four had two CTOs. Each company officer had a specific role to fill in their company, which are described in Table 11.2. These roles were intended to allow students to experience approaching a problem from different angles and with different responsibilities, focusing on team building and collaboration.

Table 11.2: Summary of student roles within companies

Officer Role	Primary Responsibilities
CEO	• Served as group leader • Coordinated meetings with the instructors/teaching assistants for extra help and investments (see section 3.1.2)
CFO	• Responsible for maintaining an accurate company budget • Responsible for placing orders with the class materials stockroom and the machinist (see section 3.1.2)
CTO	• Primarily responsible for researching and disseminating technical information regarding the project to the rest of the group

Each company submitted deliverables themed as reports they may write in industry or in academia, including a project proposal and a progress report. Expected content for each deliverable is summarized in Table 11.3. It should be noted here that the final presentation for the thermos and filter projects were PowerPoint presentations, and the final presentation for the Chem-E-Car project was a poster. Each company was responsible for producing one deliverable, and all students in a company would share the grade earned.

Table 11.3: Summary of student group deliverables

Deliverable Name	Expected Content in Deliverable
Proposal	• Clear statement of the project's overall goal • A statement of design approach • A hypothesis as to what materials and design should be best • A proposed budget for the project
Progress Report	• A diagram of the initial design and possible iterations • Preliminary test data • An updated budget for the project
Final Presentation	• Final device diagram and features of the device • Results of device testing • Final budget and cost of device

At the conclusion of each project, student companies were dissolved. New companies were formed based on student performance on the previous project. For instance, students who produced devices that performed within the top third of the class were paired with students who created devices that performed in the bottom third of the class. However, the groups were also balanced by the instructors such that they did not consist of students who performed all the same role, allowing all students to experience a new role. The changing of groups was done for three main reasons. First, it prevented disproportionately strong groups and disproportionately weak groups from persisting through the semester. Next, it allowed students to experience a project in a different company role (i.e. CEO, CFO, and CTO), as they were not allowed to fill the same role in subsequent projects. Finally, it allowed students to interact with many other students in their class, helping them build their communication and collaboration skills.

11.3.1.2 Class Economy and Material Purchasing

In order to allow students to practice the budgeting aspect of management, an in-class currency was developed (known as Chegdollars). Chegdollars could be used to purchase materials used during the design periods or to purchase the services of the class machinist, a teaching assistant, for specialty material modification using saws, drills, glue guns, etc. Students were only allowed to use materials purchased from the class stockroom to construct devices during each project, and certain materials could only be manipulated by the machinist.

Students placed orders for materials and services via paper forms that were collected by the teaching assistants.

Materials in the stockroom were priced in accordance to perceived usefulness in each project. For example, in the thermos simulation, students could buy a paper cup for 10 Chegdollars, a Styrofoam cup for 30 Chegdollars, and a block of Styrofoam for 50 Chegdollars. These limitations were imposed to encourage student creativity, as students had limited access to funds and they were incentivized to produce low-cost (in Chegdollars) devices (see section 3.2). This element encouraged students to plan their designs thoroughly, as spending most of their budget at the start of the task would either limit student options for iteration or require that students find other in-game sources of Chegdollar funding.

In the event that a company ran out of Chegdollars, they had an option to pitch to an "investor" (in this case, the instructor) for more Chegdollars. This element was included to make the economic aspects of the class less punitive if a company's design did not work as expected. The meeting could be informal, but students needed to effectively articulate how much extra money they needed and what exactly they intended to do with the money. It is up to the investor to decide if the students have effectively delivered their argument. The pitch meeting with the investor was designed to promote students' communication skills; students who articulate their points more effectively often earn more Chegdollars, and there are no negative ramifications of a failed pitch beyond not earning the desired Chegdollar amount.

For the final project, the Chem-E-Car, students were given no initial Chegdollar budget. Instead, students needed to prepare a short pitch presentation to be given to a panel of investors (the instructor and teaching assistants). Students had to show a proposed schematic, give an expected budget, and articulate what aspects of their design made them a desirable investment. Each team was then assigned two investors, who not only provided additional funding via pitch meetings, but would additionally serve as mentors during the design periods. Investors could help students refine their car-launching technique or ask leading questions to

guide their groups when they got stuck. The investor system benefitted both students and the instructors and teaching assistants; students were guided through the most complicated project and the teaching assistants were able to get to know the students on a more personal level. Many teaching assistants stated that they enjoyed this element of the course.

11.3.2 Competitive Game Elements

It was determined early in course development that student grades should not be tied directly to the results of the final device test, as students should be primarily be graded on their design methodology and quality of deliverables. However, there was still a desire to motivate students to produce high-quality devices and foster competition between companies, which would be present in a business environment. The device competition elements were turned into a game-based extra credit system, where students could earn additional non-grade points called reputation for creating devices that performed well or met other goals. A sample of the reputation awards for the Chem-E-Car simulation is shown as Table 11.4.

Table 11.4: Sample awards and their reputation values for Chem-E-Car

Award Title	Description	Reputation Earned
Most Accurate Car	During final test, the company's car was closest to the target	34
Fastest Car	During the final test, the car had the fastest linear velocity	33
Most Fuel Efficient	During the final test, the car traveled the farthest relative to the mass of reagents used	33
Best Overall Performance	A weighted average of the previous three categories	100
Best Presentation	Best presentation as voted by the instructor, teaching assistants, and the rest of the class	10
Most Creative	Awarded to the car that the students in the class have voted most creative	10
Lowest Car Cost	The final car has the lowest material cost in the class	15
Top Third	Awarded to all cars that finished in the top third of overall performance	100
Middle Third	Awarded to all cars that finished in the middle third of overall performance	85
Bottom Third	Awarded to all cars that finished in the bottom third of overall performance	70

Note that even students who did not produce cars that performed in the top third of the class were able to earn some reputation from participating in the competition. Furthermore, there are several awards that are not tied to the performance of the car, such as Best Presentation and Most Creative that allow more ambitious designs to be rewarded by their classmates. At the end of the semester, student reputation dictated the amount of extra credit grade points earned by individual students, as shown in Table 11.5. Extra grade points scaled nonlinearly with reputation points, incentivizing students to earn as many as possible by creating high-quality devices during the projects. These rewards were balanced in such a way such that the majority of students earned at least one grade point from their Reputation point totals.

Table 11.5: Conversion table for reputation points to bonus grade points (in a class graded out of 1000 grade points)

Final Amount of Reputation Points	Extra Grade Points Earned
Less than 300	0
300-349	1
350-399	3
400-449	6
450-499	10
500-549	15
550-599	21
Over 600	28

Students maintained their own reputation totals throughout the semester. When companies were dissolved and reformed, each individual student was able to keep all reputation points they had earned during the semester thus far. Penalties for violations of simulation rules (such as using outside materials) or for minor safety violations (such as not wearing safety goggles when directed) were incurred in a loss of reputation points (or loss of experience points, if the violation was severe enough to merit that deduction).

11.4 Assessment

Assessment of these methods was primarily based on student attitudes. Students took surveys during the first week of class asking them to rate how they felt about the project elements, simulation elements, and game elements of the course on the Likert scale. Students

were also asked to rate how comfortable they felt with certain aspects of the class, such as how comfortable they felt working in groups and how comfortable they felt with public speaking, on the Likert scale. Students were given the same survey during the final week of the course to assess how their attitudes had changed after completing the three projects. The pre-survey was completed by 65 students, and the post-survey was completed by 62 students.

Furthermore, teaching assistants and the instructor observed students closely during design periods to see how companies were approaching each project and which students were contributing most to each design. Teaching assistants often engaged students in conversation, asking students for their opinion on the projects, simulation elements, and course overall while giving advice on how to approach the projects.

In an effort to gauge student learning as a result of the projects, pre- and post-project quizzes were given. However, students often scored highly on the pre-project quizzes, and differences between the two quizzes were not statistically significant. Ultimately, to gauge the initial impact of this course on the students, the instructor of the first sophomore-level class students take in Chemical Engineering (Introduction to Chemical Engineering) was asked to comment on how the class who had experienced this iteration of the Foundations of Engineering course performed to the previous three classes of the course that had a more lecture-based foundations course. This information will help guide the Foundations of Engineering course and will lead to a more formal assessment of student learning in the future.

11.5 Summary of Student Experiences

On both the pre-survey and post-survey, students were given several statements and were asked to assess their agreement with them on the Likert scale. The vast majority of students agreed to at least some extent with statements such as "This class is different from others I have taken in the past" on the pre-semester survey. On the post-semester survey, 50 out of the 62 students surveyed strongly agreed that attending the design office hours felt mandatory for completing the projects. This result is substantiated by the observations of the

teaching assistants observing the in-class design time. Many of the student companies did not appear to use this time efficiently, as it was difficult for teaching assistants to fill the high volume of materials orders during class time. Students were allowed to spread out across a nearby lobby, making it difficult to assure that students were staying on-task during the entire design period. Overall, however, 36 of the 62 student respondents indicated they agreed to some extent with the statement “I enjoyed this class overall,” with 18 students neither agreeing nor disagreeing with the statement, and 8 students somewhat disagreeing with the statement.

In order to assess student attitudes toward their own skill development in the course, responses to some of the pre- and post-semester survey were compared. Specifically, student attitudes toward two statements related to their comfort levels with collaboration (“I enjoy(ed) working in groups”) and communication (“I am comfortable presenting technical information to the class”) were examined. The attitudes of the students are summarized in Figures 11.1 and 11.2.

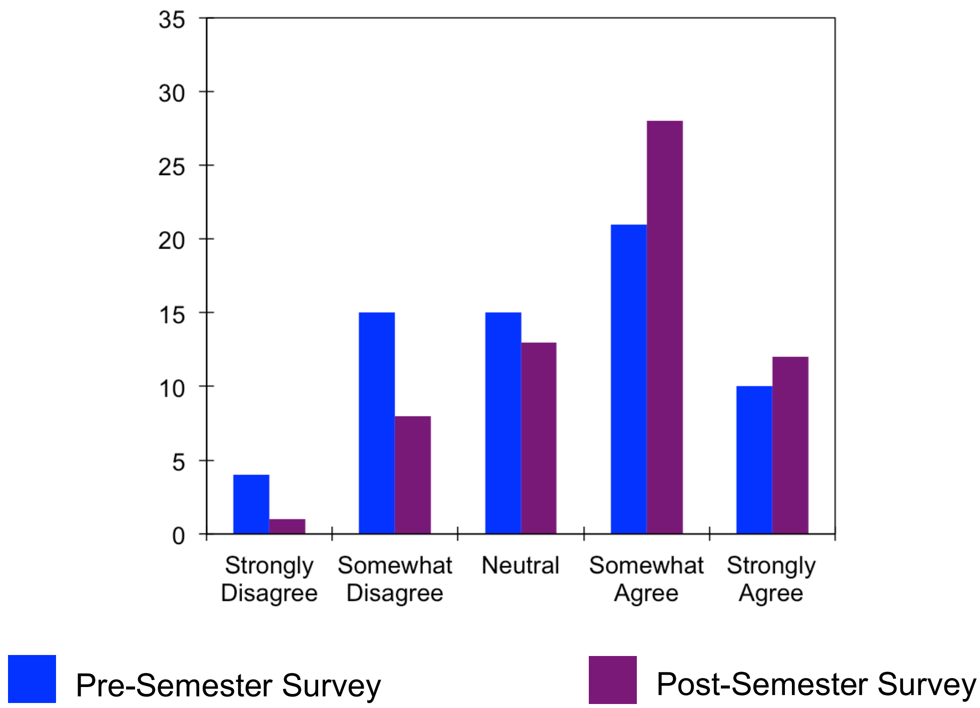

Figure 11.1: Student self-perceived responses to the statement “I feel comfortable presenting technical information to the class” (Likert scale), where the y-axis represents the number of students.

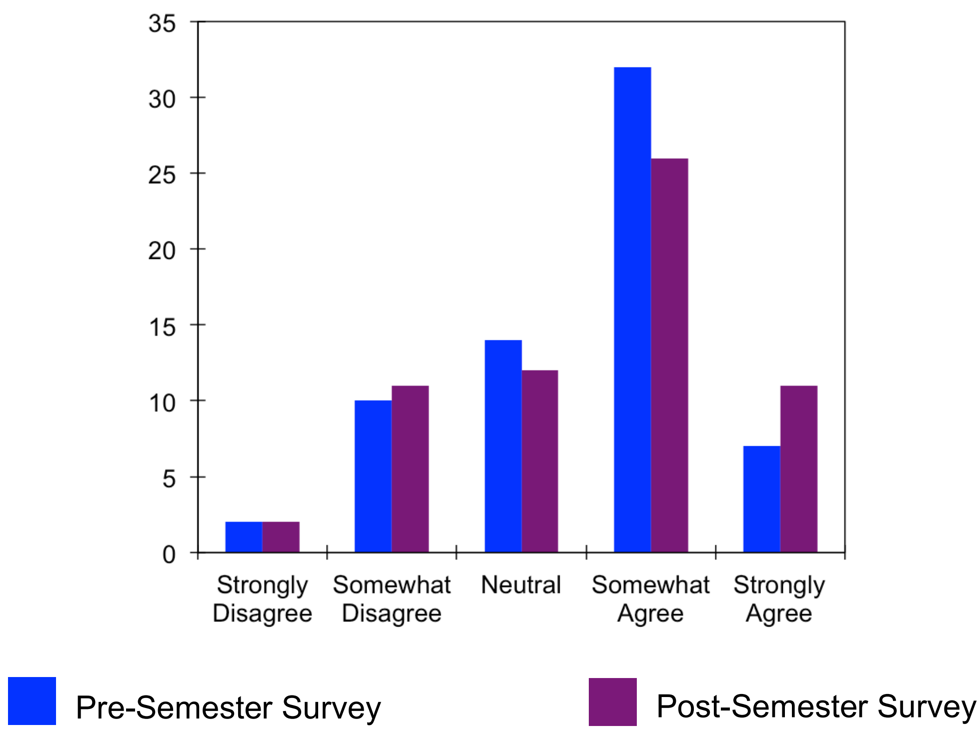

Figure 11.2: Student self-perceived responses to the statement “I enjoy(ed) working in groups on projects” (Likert scale), where the y-axis represents the number of students.

Figure 11.1 indicates that, compared to the start of class, 10 students perceived that they felt more comfortable presenting data in front of the class at the end of the semester, when they had presented their designs to the class three times. This increase may also be attributed to practicing communication skills in meetings with investors. Figure 11.2 indicates that students generally had greater self-perceived positive feelings toward working in groups at the end of the semester compared to the beginning. This result is encouraging, as the class has made a positive contribution toward students' attitudes toward group work, preparing them for usual levels of group work as they progress in the engineering curriculum.

Students were able to write general comments on the post-semester survey. The feedback was mixed, with some being very positive and others being very negative. The positive feedback stated that students appreciated the ability to gain hands-on design experience early in the curriculum. One student wrote, "The projects were an eye-opening way to look at chemical engineering – it was definitely a proper intro class for the major." Negative comments focused on the time commitments required for the course, as well as the content covered during the lecture and how it related to the projects. Another student wrote, "I was not clear about what was being taught and what [the instructor] was expecting us to learn." Moreover, the comments revealed that many students did not realize that the reputation tasks were extra credit and were concerned that they would have their grades reduced if their devices did not perform well. Addressing these comments was high priority when refining the class for the next offering.

Additionally, the students were asked to evaluate their attitude toward the simulation and game elements in the post-semester survey. The results of this poll are summarized in Table 11.6.

Table 11.6: Student attitudes toward the business simulation and game elements, evaluated on Likert scale

Number of students responding	**Disliked a Lot**	**Somewhat Disliked**	**Ambivalent**	**Somewhat Liked**	**Liked a Lot**
Companies and Roles	1	5	18	25	13
Changing companies after each project	3	7	9	27	16
Using Chegdollars	1	10	14	28	9
Purchasing materials	1	5	10	34	12
The Chem-E-Car Investor System	2	7	8	21	23
The Reputation extra credit system	2	4	11	24	21
Performance-based Reputation awards	3	2	10	26	20

Student attitudes toward the game elements were significantly more positive than their attitudes toward the class overall. The majority of students at least somewhat liked all of the game and simulation elements. The most popular elements included the Chem-E-Car system of personal investors and the reputation extra credit system, likely due to the additional personalized help and the additional grade points these systems provided. These results indicate that these systems are effective at generating student interest and should be bolstered with improved course content.

Finally, discussions with the instructor of the sophomore-level Introduction to Chemical Engineering course indicated that these students did not seem significantly more or less prepared for his course. Furthermore, the instructor did not indicate that the grades of students who took the project-based course were significantly different from the grades of those who did not. The instructor indicated that, like all sophomore classes he has encountered, the students struggled with using Microsoft Excel to analyze data and with unit conversions. This feedback was used to help shape the course content in future offerings.

11.6 Spring 2015 Iteration

In order to address student feedback, the course has been adapted for the Spring 2015 semester. The course content has shifted to emphasize the acquisition and analysis of data using software packages like Excel, and data presentation using proper technical writing techniques and PowerPoint skills is explained to and expected of all students. The class now meets twice a week for 75 minutes each. The first period is a lecture period, which is based on information students will find most useful at that stage of the project. The second period of the week is a dedicated to design, where students are expected to build a simple prototype and test it at least three times for reproducibility. Rather than have several short design office hours, an optional four-hour design period has been made available once a week if students need additional build and test time. The design period is long enough to accommodate students with late afternoon or evening classes. Furthermore, a non-design office hour period is offered at a separate occasion for students with questions about the course content.

As many students felt they did not have enough time to complete projects, one of the projects was removed. To determine which project to remove from the new iteration, student feedback, shown in Figure 11.3, was considered. The majority of students (40) selected Chem-E-Car as their favorite project, citing that it was either the one they considered to be the most fun or the one they learned the most from. Conversely, the water filter earned the most votes for the project students liked the least. Students often cited that the project was confusing, and that lecture material did not help with the filter project as much as it did for others. As the filter was the least popular project among students and by far required the most material preparation, the project was dropped for Spring 2015. With the removal of the filter, students are able to spend 4-5 weeks on a given project. This change also allows for the first design period of a project to be a no-cost "play" period, where companies can perform experiments using materials they will use to construct their device. Not only are students allowed to then make informed

decisions about materials, but they are allowed and encouraged to practice good experimental techniques when taking their data.

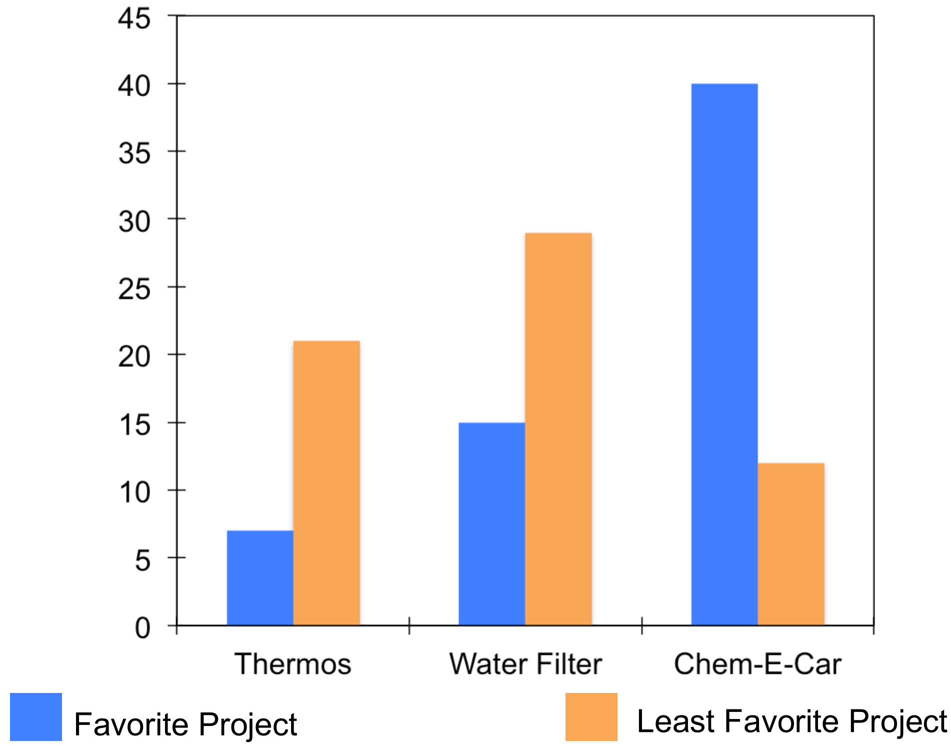

Figure 11.3: Favorite and least favorite projects, as voted by students. Y-axis represents the number of students.

Table 11.7 shows how grades are determined in the Spring 2015 iteration of this course. Given the extra time students now have, the deliverables have changed accordingly. The proposal is now based off the data students gather during the initial "play" period. Students must synthesize the data and state how it will apply to their initial design. The following week, after students have built and tested their first design, students must produce an initial progress report. In this report, students present the data from their first design and express how they intend to iterate on it. The iteration report follows, where students test their iteration, discuss how it differed from their first attempt, and then conclude by considering what elements of each design they wish to incorporate in their final design. The presentations are the same as the previous iteration of the course, and deliverables are predominantly graded using rubrics that

emphasize student effort and critical thinking. Students are provided with report templates that explicitly state what elements are needed in each report.

Table 11.7: Assignments as contributors to student grades in the Spring 2015 semester

Item	Points per Item	Number of Items	Total Points (Percentage of Grade)	Notes
Proposals	100	2	200 (14.3%)	20% individual, 80% full report
Initial Progress Report	100	2	200 (14.3%)	20% individual, 80% full report
Iteration Report	100	2	200 (14.3%)	20% individual, 80% full report
Final Presentation	100	2	200 (14.3%)	Team grade
Peer Assessment	20	2	40 (2.8%)	Individual grade
Homework	20	10	160 max. (11.4%)	Individual grade
Midterm Exam	200	1	200 (14.3%)	Individual grade
Final Exam	200	1	200 (14.3%)	Individual grade

In order to give students more individual control over their grades, a new grading scheme was developed for the written deliverables. Each deliverable is worth 100 points and contains four 1-2 page sections, which include an introduction, a detailed device summary and diagram, a discussion of test results, and an update of the company budget and planned next steps. Each student in a company must claim ownership of one of the pages and should be primarily responsible for that page's content. Each page is worth 20 points individually, and one completed report is worth 80 points. To reach the complete 100 points, students earn up to 80 points from their company's completed report. Each student then earns up to 20 points based on the score from their individual page. This system is represented graphically as Figure 11.4. Students are now directly responsible for 40% of their grade for each deliverable.

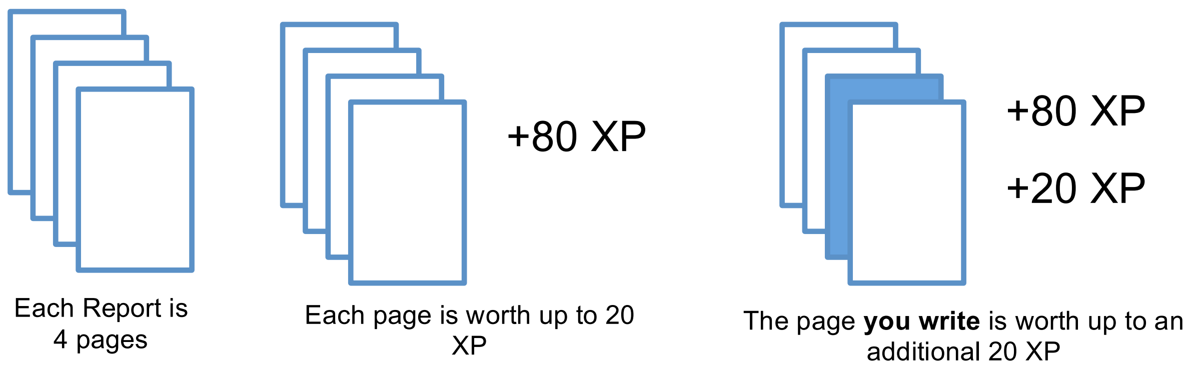

Figure 11.4: Alternative report grading method to allow individual students to have more of an impact on their personal grades, as presented to students.

Previously, the deliverables were graded solely by one instructor of the course, which was a heavy burden on that instructor. By splitting deliverables into four sections with detailed templates and rubrics, grading can be spread to multiple instructors and/or teaching assistants. To assure consistency of grades, each grader is responsible for grading the same section for each deliverable for the entire semester. With this system in place, two instructors and two teaching assistants are able to grade deliverables for nineteen student companies in an afternoon. In order to assure that students gain experience writing a variety of sections and graders, students are not allowed to write the same section for two consecutive deliverables. More importantly, this system actively encourages students to communicate the strengths and weaknesses of sections they have already written to their teammates, enabling an atmosphere where students can teach their peers and reinforcing what they have learned. This communication is essential as it helps all teammates improve the quality of their sections, which will in turn help all students in the group.

Quizzes have been replaced with homework, which are one or two simple problems that give students additional practice with course concepts beyond the projects. These homework questions allow students to practice with information given during lectures and assist students with exam preparation. The way homework is graded reflects an aspect of game-based learning allowing students to customize their experience. There are 200 points available from homework in a semester, but students can only earn a maximum of 160 points. This system

allows students some leeway in their homework assignments, as points lost on an earlier assignment can be made up by completing a later one. This system also discourages students from letting homework overwhelm the projects, as there are ample opportunities to make up lost points.

Other changes were made to streamline the simulation and game elements. It was clarified to students early on that device performance only impacted extra credit, which was changed from “reputation” to “net worth” to reflect the business theme. The materials ordering system was streamlined, moving from a paper order form to an online Google Form tied to a Google Spreadsheet that only the instructors and teaching assistants could access. The spreadsheet automatically tracks what materials are ordered by each company, allowing for the teaching assistants to easily fill orders as they are placed between classes and track each company’s budget. Another element for the Spring 2015 semester was optional design challenges, where students could impose limitations on their final design for extra net worth. For example, if students complete a thermos without using a cup, which is often the most convenient and cost effective method, they will earn a small amount of net worth. Any number of students can attempt these challenges, which are designed to promote creativity by removing obvious solutions and increasing difficulty of the projects if students desire it.

11.7 Spring 2015 Mid-Semester Evaluation

At the time of writing, students have completed one project and, thus, one complete round of deliverables. At this time, students were surveyed for their opinion about various components of the class, the new system of deliverables, the business elements, and their opinion of the class overall. Of the 69 students in the course, 66 completed the survey.

In general, students were mixed in their opinion of the course overall. While many students (32) like the course to some extent (either strongly or somewhat), some students (24) dislike the course to some extent primarily due to the perceived harshness of grading, particularly on homework assignments. As this class is the students’ first in engineering, the

authors attribute this attitude to an adjustment period where students are learning and understanding instructor expectations. The fact that the students are improving with each deliverable supports this hypothesis. Students showed improvement on the second deliverable, with the average section grade rising from 15 ± 3 to 16 ± 2 XP out of a possible 20. While this change is not statistically significant, the average did rise slightly and the range of grades has become narrower.

The majority of student respondents (53) said that they prefer the new deliverable system to a more traditional group work system where all students work on the report together and share the same grade, with 28 strongly preferring the new method. Initially, students appeared to struggle with the first deliverable as they were becoming acclimated to the system of deliverables, and some students did not communicate effectively with their group members. Additionally, students appeared to struggle with some of the finer points of each deliverable, namely proper data presentation with error analysis and technical writing, which prompted short in-class reviews of those topics during the lecture period. As stated previously, student grades continue to steadily improve as they acclimate to the class and these systems. Most of the students (48) agreed to some extent with the statement "I feel I am gaining useful skills in this class." The majority of students (50) agreed with the statement "I communicate the reviewer comments from my graded deliverable sections to my teammates," indicating that the students are using the peer education element of this deliverable structure.

11.8 Concluding Remarks

While student feedback to this course has been mixed, the student opinion of the game and simulation systems added to a project-based freshman design course was very positive. The business simulation and game elements appear to have a positive impact on student attitudes toward communicating information and working in groups. Many students indicated they feel a project-based class of this nature in the first year of college was beneficial to their understanding of engineering as a field and engineering design specifically. While there are

several improvements that are currently being implemented into this system, student feedback to the business game elements was highly positive. These early trends show there is promise in combining project-based, business simulation, and game-based learning elements to engage students in a freshman design course.

Additionally, as this study has primarily relied on survey data, a more rigorous method of assessment is currently being devised. The students participating in the Spring 2015 offering of this course will have their performance and retention tracked through the sophomore-level courses. The performance of these students will then be compared to the performance of a control group of students in the Spring 2016 offering of this course, which will be project-based but will lack the simulation and game elements.

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CHAPTER 12

SUMMARY AND RECOMMENDATIONS

12.1 Concluding Remarks

The first goal of this work was to modernize the senior-level chemical engineering laboratory course by building experiments that stress core chemical engineering concepts in a modern context. This goal was sought in order to present chemical engineering material in a practical way that relates to emerging industries in which students may seek employment or research opportunities post graduation. To meet this goal, three experiments were fully developed and implemented, with one additional experiment proposed and awaiting final testing before the experiment can be deployed to students. These experiments introduce students to the areas of membrane separations, osmotic power generation, microfluidics, and rapid prototyping while teaching core concepts from fluid mechanics, mass transport, reaction kinetics, and thermodynamics. While not developed directly as part of this dissertation, the laboratory curriculum was further augmented with experiments related to biochemical engineering, pharmaceuticals and drug delivery, and chemical vapor deposition to expand the chemical engineering topic areas presented in the laboratory as well.

Students have reacted positively to these experiments, often preferring the new experiments to the more basic laboratories presented in the junior-level laboratory courses, and consistently demonstrate their understanding of the base chemical engineering concepts in their laboratory reports. Furthermore, these experiments are designed for easy implementation in a variety of classrooms and laboratories, increasing their ability to be translated to other universities. Several of the experiments developed as part of or parallel to this work, such as the forward osmosis experiment and the chemical vapor deposition experiment, originated in the University of Connecticut chemical engineering teaching laboratory and are now present in the laboratory curricula at other universities.

The secondary goal was to improve student engagement with the laboratory by using gamification to provide students with additional ways to participate in the class and incentivize the formation of habits that make them effective in the laboratory. The first implementation motivated students to complete optional tasks related to data analysis and broader impacts by rewarding them with game points and badges. A more advanced implementation was later used that tasked students to complete tasks to defend the points they had accumulated until the end of the semester, causing interested students to participate in the tasks through the duration of the semester to maximize bonus grade points. Students reacted positively to these systems, and participation in the game was significantly increased when the second method was employed. Similar game-based systems were used to augment a newly structured first-year engineering design course; these systems were designed to encourage students to think critically, foster creativity, and to communicate and collaborate with others. While the first-year students had mixed opinions on the course content, they were much more positive about the inclusion of the additional elements. Further refining of these elements has improved the quality of the course in a subsequent semester.

While it is unclear if these game-based systems improved student comprehension due to lack of formal external assessment, discussions with alumni indicate that the game systems made the laboratory course more memorable to the students. The uniqueness of the courses may make the material presented in the courses easier for students to recall, but this hypothesis merits further study. However, based on early implementations, it is apparent that gamification should be used carefully, and overuse will diminish student interest and participation.

In department exit interviews with graduating seniors since these changes have been made, the majority of students present praise the senior-level laboratory both in terms of the types of experiments they are allowed to perform and the way the course is taught, indicating that the efforts described in this thesis are helping to improve student attitudes toward the capstone laboratory. As the laboratory is forced to grow to accommodate larger class sizes, it is

vital to develop chemical engineering experiments framed in contexts relevant to current students while allowing students different avenues to engage the material in addition to experimentation.

12.2 Summary of Contributions & Applications

This work has resulted in several contributions to chemical engineering instructional laboratories, including:

- The development, construction, and implementation of mobile crossflow reverse and forward osmosis systems (presented in Chapters 3 and 4). These experiments allowed students to understand the link between fluid mechanics and mass transport in the context of membrane desalination tests. These apparatuses have been used as separate experiments and together as a longer experiment that examines two different driving forces for membrane desalination. System designs and laboratory documentation for these experiments have been disseminated to multiple universities for use in their teaching laboratories.
- The initial testing and development of an experiment based on principles of pressure retarded osmosis and osmotic power (presented in Chapters 5 and 6). The data presented in Chapter 6 represents one of the first experimental demonstrations of high membrane power density achieved with commercial forward osmosis membranes via manipulation of draw solution concentration and temperature. Chapter 5 outlines the pilot-scale osmotic heat engine system that is planned for installation in the University of Connecticut chemical engineering instructional laboratory, which will serve primarily as a research tool but can also teach students concepts related to solution thermodynamics, process thermodynamics, and pilot-scale separations. When completed, this system will be the first osmotic heat engine that has been assembled at the pilot scale.
- The development and implementation of a reactor design experiment that allowed students to design, print, and test millimeter-scale tubular reactors (presented in Chapter

7). Students compared their devices to models developed in COMSOL Multiphysics to evaluate how reactor dimensions and geometry impacted reaction conversion in the laminar flow regime, forcing students to synthesize knowledge of fluid mechanics, mass transport, and reaction kinetics. This experiment is the first in the laboratory curriculum to allow students to practice iterative design and will be one of the first chemical engineering laboratory experiments in open literature to use rapid prototyping as a tool to teach chemical engineering core concepts.

This work has also contributed to the study of game-based learning in engineering laboratory curricula in the following ways:

- The creation of an easily customizable framework for a gamified engineering teaching laboratory. The system moves beyond a basic badges, points, and leaderboard game structure to one that encourages students to participate in tasks that will improve their data acquisition, data analysis, and understanding of broader impacts of their experiment. The system encourages and rewards consistent student participation through the duration of the class, and students can be motivated by both points and the development of their own in-game character. The methods proposed are highly adaptable to the needs of an instructor; systems may be subtracted or enhanced as the instructor deems fit, making the system easily disseminated.
- The enhancement of a project-based first-year engineering design course with game elements such as a company structure, currency, and design challenges. These systems augment the benefits of project-based courses by giving students additional ways to practice soft skills such as communication, creativity, and critical thinking.

12.3 Future Directions

12.3.1 Future Work on the Osmotic Heat Engine Experiment

While many of the key components of the osmotic heat engine, such as the membrane and the draw solute absorber, have been selected and ordered, the apparatus requires

assembly. Once assembly is complete, the system should be tested to evaluate the base efficiency of the engine. After the system has been run and its capabilities are known, students may begin working on the equipment as part of a senior-level laboratory. Students can vary draw solution concentration, membrane operating pressure, and solution flow rates to observe the impact of these variables on power generated by the turbine and steam used in the stripping column. Ultimately, students will need to determine the overall efficiency of the process and compare it to the Carnot efficiency.

Once the baseline tests have been performed, the process should be optimized. The temperature of the steam used should be lowered to 40 – 60 °C to better represent the low-quality heat sources the osmotic heat engine would be used to harness in an industrial setting. Additional stripping or absorbing units may need to be installed to accommodate changes in fluid flow. Imposing a vacuum on the steam or using a steam generator could achieve these temperatures. Instrumentation could also be upgraded to incorporate automatic process controls, which would assist in reaching and maintaining steady state in the process. Students can also perform simple upgrades, such as changing tubing or instrumentation, under instructor supervision, giving them experience assembling and disassembling equipment.

Improvements to the efficiency of the engine can also be made through changing test conditions. High power densities are required to reach high engine efficiencies. This system allows the evaluation of membrane modules, rather than flat-sheet coupons, designed specifically for pressure retarded osmosis. These modules may be spiral-wound or comprised of hollow fiber membranes. The falling-film stripper is also designed to interface with a pilot-scale forward osmosis desalination system that is currently in development, presenting opportunities to evaluate these membranes in forward osmosis as well.

12.3.2 Future Work for 3D Printer Experiments

The 3D printed reactor experiment can be expanded to encompass different reactions and reactor types. For instance, while the saponification of isopropyl acetate with sodium

hydroxide repeats a reaction that students have studied in the junior-level lab, other reagents will yield different experiences. A reaction using a dye and a bleaching agent, such as methylene blue and ascorbic acid, would provide students with a reaction they could see visually, and extent of reaction could be assessed via spectrophotometry. Likewise, students could experiment with different types of reactors other than simple channels. Students in the past attempted using static mixers, but a circular channel could also be devised to allow for a small stir bar to be inserted. While this reactor would be difficult for students to model in COMSOL, it would more closely mimic a CSTR.

The 3D printer can also augment pre-existing experiments in the laboratory to allow for more iterative design elements in the course. Students can design loose and structured packing for a miniaturized carbon dioxide absorption experiment, examining how the shape and surface area of the packing impact the mass transfer coefficients. Students performing the reverse or forward osmosis experiments could design channel supports to explore how mass transfer boundary layers are formed in the presence of additional turbulence imposed by the supports. Pressure drop through each membrane cell could also be a factor in need of study. The drug delivery experiment could also benefit from the 3D printer, as molds for alginate beads could also be created, allowing students to evaluate the impact of geometry and surface area on the rate of tartrazine released. Students could also use the printed reactor channels and a heat or cooling source to perform small-scale heat exchanger experiments. However, this experiment would require substantial testing, as the cured printer resin has low tolerance to high temperatures.

12.3.3 Future Work on Gamification in Engineering Classes

As mentioned previously, formal external assessment is needed to assess claims that the system proposed in this dissertation has a positive impact on student learning, rather than simply improving student attitudes toward the capstone laboratory. These assessors could quantitatively evaluate student performance in the course while remaining objective. Ideally, the

assessors would also be able to perform qualitative assessments of student attitudes and how students are participating in the course.

At least one semester of a future course should be run without the game elements to serve as a control group. Data for a control group was not collected in these studies as rising juniors had already learned about the game as they arrived in the senior-level lab, setting a level of expectation. If these expectations were not met because the game was not run, this may result in a false positive in favor of the game. In a control group, students will be notified of the same optional tasks associated with the game-based course, but should receive no point-based reward for completing them. Participating, attitudes, and learning could then be assessed for this group, which would then be compared to subsequent game-based offerings of the course to observe any significant changes.

Once evaluation methodology is solidified, a study involving students from multiple universities should be performed both to increase the sample size of the study and to evaluate how students from a variety of backgrounds interpret the game-based course structure. Participating instructors must be sure to use the same game methodology and assessment methods at each institution. This study will help refine some of the game-based teaching strategies that are beginning to be employed in engineering education.