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Current State of the Assets in the Chemical Engineering Laboratory at Rose-Hulman Institute of Technology and Their Use in the Undergraduate Laboratory Course Sequence

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Current State of the Assets in the Chemical Engineering Laboratory at Rose-Hulman Institute of Technology and Their Use in the Undergraduate Laboratory Course Sequence

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of

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by

Matthew Elliott Adams

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ROSE-HULMAN INSTITUTE OF TECHNOLOGY

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PASSED ___X___ **FAILED** ______

ABSTRACT

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M.S.Ch.E.

Rose-Hulman Institute of Technology

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Current State of the Assets in the Chemical Engineering Laboratory at Rose-Hulman Institute of Technology and Their Use in the Undergraduate Laboratory Course Sequence

Thesis Advisor: Dr. Atanas Serbezov

The Chemical Engineering Laboratory, also referred to as the Unit Operations (UO) Laboratory, is integral to any undergraduate Chemical Engineering curriculum as it provides students with the opportunity to gain practical and hands-on experience with processes that are commonplace throughout industry. The Chemical Engineering Department at Rose-Hulman Institute of Technology prides itself in providing its students with a practical education that will allow for an easy transition into industry as well as continued success throughout the students' careers; as such, the assets in the Chemical Engineering Laboratory space and their use are paramount to this objective.

The Chemical Engineering Department at Rose-Hulman recognizes the importance of the Chemical Engineering Laboratory sequence; therefore, the Chemical Engineering Department has initiated a focused discussion on the role of the Chemical Engineering Laboratory in the undergraduate curriculum. This discussion focuses on the educational objectives and student outcomes offered by the Chemical Engineering Laboratory sequence. In order to inform this discussion, it is necessary to provide the Chemical Engineering Department with an organized record of the assets presently available in the Chemical Engineering Laboratory and their current use in the undergraduate laboratory courses. Additionally, guidance is needed for future updates and expansions in the Chemical Engineering Laboratory should be documented as determined through faculty interest in the Chemical Engineering Department and through comparison to other similar institutions. The results gathered offer a solid foundation for the Departmental discussion on the future of the Chemical Engineering Laboratory in the curriculum and can be used to determine where the current laboratory model has both successes and areas for improvement.

Keywords: Chemical Engineering, Chemical Engineering Laboratory, Unit Operations Laboratory, Chemical Engineering Undergraduate Laboratory Courses, Asset Management

DEDICATION

Throughout my life, I have had several amazing and influential role models, mentors, and teachers. My grandfather, Merritt E. Adams, held each of those three titles of role model, mentor, and teacher to me. He taught me the importance of education and piqued my interest in mathematics, science, and engineering. I owe a great deal to my grandfather as I know I would not have experienced the success I have had thus far without his encouragement and words of wisdom. I would like to dedicate this thesis to my grandfather, Merritt E. Adams, as well as to all of the individuals who have served as a role model, mentor, and/or teacher to me as I would not be where I am today without their guidance, mentorship, and their ability to impart their knowledge upon me.

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I would further like to thank the Chemical Engineering Department's laboratory technician, Frank Cunning, as there is no possible way I would have been able to accumulate the necessary information without him. Dr. Heather Chenette, Dr. David Henthorn, Dr. Kimberly Henthorn, Dr. Scott McClellan, Dr. Gregory Neumann, Dr. Adam Nolte, Dr. Irene Reizman, and Dr. Marissa Tousley have my complete and sincere gratitude for their assistance as this project evolved and began to take shape.

A huge thank you also goes out to the many friends who I have made throughout my time at Rose-Hulman, as I would not have had nearly as much fun, procrastinated to the extent that I did, or had the success that I have experienced thus far without your friendship and support. The Rose-Hulman family is a real thing, and I am beyond proud that I can call myself one of its members.

My biggest thank you goes to my family, Mom, Dad, and Josh, for supporting me as I pursued my education and dream at Rose-Hulman. I could not have survived or succeeded without your undying support, advice, humor/sarcasm, and above all else, love.

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LIST OF ABBREVIATIONS

ABET	Accreditation Board for Engineering and Technology
AY	Academic Year
CAD	Computer-Aided Design
DCS	Distributed Control System
DMA	Dynamic Mechanical Analysis
DSC	Differential Scanning Calorimeter
FTIR	Fourier Transform Infrared Spectrometer
P&ID	Piping and Instrumentation Diagram
SOP	Standard Operating Procedure
UO	Unit Operations

1. INTRODUCTION

Rose-Hulman Institute of Technology, or Rose Polytechnic Institute, as it was named between 1875 and 1971, was chartered under the laws of the State of Indiana on September 10, 1874 as an institution "for the intellectual and practical education of young men" [1]. In 1889, it granted the first Chemical Engineering undergraduate degree in the United States [2]. The Chemical Engineering Laboratory, also referred to as the Unit Operations (UO) laboratory, has always been a key component of the undergraduate Chemical Engineering program, in keeping with the Institute's conviction that students learn best by doing.

The Chemical Engineering Laboratory moved to its current location in 1984 when Olin Hall was constructed with funds from the Olin foundation. At present, the laboratory facilities consist of two interconnected centrally located large bays and eight smaller rooms situated on the periphery of the large bays. A number of pilot scale Experimental Setups were designed and built immediately following the move to the new facilities in 1984 [2]. Since then, the laboratory equipment has been continuously updated. Currently, there are nineteen (19) different experimental modules available for undergraduate laboratory projects as well as forty-eight (48) Analytical Instruments that support undergraduate laboratory projects and various research projects. Most of the updates in the laboratory equipment have occurred in an ad hoc manner, driven primarily by equipment breakdowns, faculty interests, and available funding.

At the beginning of AY 2016-17 the faculty in the Chemical Engineering Department initiated a focused discussion on the role of the Chemical Engineering Laboratory in the undergraduate curriculum, more specifically the educational objectives and student outcomes. In the course of this discussion the Chemical Engineering Department realized that information about the laboratory equipment and its use was not readily available and easily obtainable. Basic information, such as floor plans with up-to-date layout, did not exist. Even though the assets in the Chemical Engineering Laboratory constitute a significant investment, there was no formal system for tracking and documenting the usage of the equipment. There were no formal plans for operating, maintaining, upgrading, and disposing of assets.

The purpose of this work is to fulfill the immediate need of providing an organized record of the assets presently available in the Chemical Engineering Laboratory and their current use in the undergraduate laboratory courses. The comprehension of the information is facilitated by breaking down the equipment list using sets of categories related to asset management and learning objectives. The breakdowns by categories are aimed at elucidating the various ways in which experiments are used in the undergraduate laboratory.

Another goal of this project is to provide guidance for future updates and/or expansions in the Chemical Engineering Laboratory. A comparative survey with five similar programs points out the similarities and differences in the offered undergraduate laboratory projects. In addition, all faculty in the Chemical Engineering Department have been interviewed for their interests in developing new or modifying existing projects.

The results presented in this work offer a solid foundation for the Departmental discussion on the future of the Chemical Engineering Laboratory in the curriculum. They can be used to identify elements of the current practice that are working well and should be retained should the undergraduate laboratory courses be restructured in the future. The results can also be used to pinpoint and correct inefficiencies or deficiencies in the current laboratory model.

2. BACKGROUND

2.1 Importance of the Laboratory Courses in the Chemical Engineering Undergraduate Program

Instructional laboratories have been an essential part of undergraduate engineering programs since the very beginning of engineering education. The purpose of laboratory work is succinctly described in a 1986 publication by the National Research Council:

> “The undergraduate student should become an experimenter in the laboratory, which should provide him with the basic tools for experimentation, just as the engineering sciences provide him with the basic tools for analysis. It is a place to learn new and developing subject matter as well as insight and understanding of the real world of the engineer. Such insights include model identification, validation and limitations of assumptions, prediction of the performance of complex systems, testing and compliance with specifications, and an exploration for new fundamental information” [3].

The many aspects of the role of the teaching laboratory in engineering education were analyzed in the seminal paper by Feisel and Rosa [4]. The authors presented a historical overview of engineering teaching laboratories, and outlined a set of fundamental learning objectives for the undergraduate engineering courses. According to Google Scholar, this paper has been cited 999 times as of August 1, 2017 [5]. Specific applications and assessments of these objectives in the context of a Chemical Engineering Laboratory have been described by:

- Glasgow’s 2007 paper titled “Addressing the Disconnect Between Engineering Students and the Physical World,” which describes how Chemical Engineering students oftentimes have difficulty evaluating whether or not their work/answers to problem-solving exercises is/are reasonable and realistic [6]. The paper stresses the importance of pilot scale projects in the undergraduate laboratory and how said projects can be used in order to reconnect Chemical Engineering students with the physical world by "provid[ing] students with the opportunity to experience fluid forces, velocities, and frictional losses in a physically meaningful context" [6]. Pilot scale projects are discussed in further detail in Chapter 5.5 of this work. The pilot scale projects also allow students to achieve Feisel and Rosa's objective of sensory awareness, which is highlighted in the paper as one of the key objectives and will be discussed and used as the motive for a category used to categorize the assets in Chapter 6.5 [6].

- Ragusa and Lee's 2009 paper titled "A Degree-Project Approach to Engineering Education," which details the importance of connecting the Chemical Engineering curriculum to the undergraduate laboratory by having projects based around core Chemical Engineering competencies while also staying current with industry trends and academic research [7]. The concept of staying current with industry trends and academic research is one of the main motivations for Chapter 8, which addresses faculty interests in new assets. Additionally, the paper describes how Feisel and Rosa's objectives of models, psychomotor, and sensory awareness must necessarily be incorporated into projects to allow for the development of effective Chemical Engineers; consequently, the objectives of models, psychomotor, and sensory awareness are described and used as the reasoning for the selection of categories by which to categorize assets in Chapters 6.2, 6.4, and 6.5, respectively [7].
- Abdulwahed and Nagy's 2009 paper titled "Applying Kolb's Experiential Learning Cycle for Laboratory Education," which discusses how historically "[t]he impact of laboratory

education on students' learning is often not recognized"; however, "engineering graduates who are autonomous and equipped with good hands-on skills" are needed by industry, which thereby makes "knowledge gained via experience" a necessity [8]. "[K]nowledge gained via experience" can be obtained through a successful laboratory experience that incorporates projects based upon Feisel and Rosa's objectives of models, design, psychomotor, and sensory awareness, which are further discussed and used as the motives for categories used to classify the assets in Chapters 6.2, 6.3, 6.4, and 6.5, respectively [8].

- Billet, Camy, and Coufort-Saudejaud's 2010 paper titled "Pilot Scale Laboratory Instruction for ChE: The Specific Case of the Pilot-Unit Leading Group," which describes the optimal teaching methods to employ in undergraduate laboratories to best achieve Feisel and Rosa's thirteen objectives through the use of pilot scale projects [9]. Pilot scale projects are discussed in further detail in Chapter 5.5 and five of Feisel and Rosa's thirteen objectives are described and used as the reasoning for the selection of categories by which to categorize assets in Chapter 6 [9].
- Glasgow and Soldan's 2010 paper titled "Reconnecting Chemical Engineering Students with the Physical World," which details the results of implementing the pilot scale projects described in Glasgow's 2007 paper in the undergraduate laboratory and the effect said projects had on reconnecting Chemical Engineering students with the physical world [10]. The pilot scale projects successfully achieved Feisel and Rosa's objective of sensory awareness and allowed Chemical Engineering students to be more cognizant of reasonable and realistic work/answers to problem-solving exercises [10]. Pilot scale projects are discussed in further detail in Chapter 5.5 and Feisel and Rosa's objective of

sensory awareness is described and used as the motive for labels to categorize the assets in Chapter 6.5.

- Amante, Martinez-Martinez, Cadenato, Gallego, and Salan's 2011 paper titled "'Applied Scientific Method' in the Laboratory," which discusses the importance of designing laboratory projects with respect to learning objectives and learning outcomes in such a way that the corresponding Chemical Engineering subject area(s) is/are clear to students [11]. Additionally, the lack of student participation in Feisel and Rosa's objective of design is noted as a common deficiency in undergraduate laboratories [11]. The importance of the representation of each of the core Chemical Engineering subject areas is discussed in detail with respect to the assets in Chapter 6.2 and learning objectives and learning outcomes were commonly used to determine the subject area represented. Furthermore, Feisel and Rosa's objective of design will be discussed and used as the reasoning for the selection of categories in Chapter 6.3.
- Rende, Baysal, and Rende's 2011 paper titled "Introducing Professional Skills During Unit Operations Laboratory," which describes the importance of incorporating professional skills in addition to the technical skills into the laboratory experience [12]. The paper details how professional skills were implemented while still maintaining the academic rigor of the laboratory experience by emphasizing Feisel and Rosa's objectives of models, design, and sensory awareness in the projects, which are described and used as the motives for categories in Chapters 6.2, 6.3, and 6.5, respectively [12].
- Gosselin, Fauteux-Lefebvre, and Abatzoglou's 2013 paper titled "How Students Perceive the Many Roles They Must Play in an Engineering Laboratory Course," which details the various roles that students are required to experience in a successful laboratory

experience [13]. The paper stresses Feisel and Rosa's objectives of instrumentation, models, design, and sensory awareness as key objectives that must be present in pilot scale projects for a student to experience each of the various roles during the course of the project that they will experience throughout their career; consequently, pilot scale projects are discussed in further detail in Chapter 5.5 and the objectives of instrumentation, models, design, and sensory awareness are described and used as the reasoning for the selection of categories utilized in Chapters 6.1, 6.2, 6.3, and 6.5, respectively [13].

- Benson, Richmond, and LeBlanc's 2013 paper titled "Unit Operation Experiment Linking Classroom with Industrial Processing," which discusses connecting the laboratory experience with an actual real-world example through an open-ended project in order to give students relevant industry experience [14]. The advantage of using an actual real-world example is that students "challenge their ability to apply knowledge learned in the classroom to a…system that would be comparable to that found in industry"; therefore, this project emphasizes Feisel and Rosa's objectives of instrumentation, models, psychomotor, and sensory awareness, which are discussed and used as the motives for categories in Chapters 6.1, 6.2, 6.4, and 6.5, respectively [14].
- Kubilius, Tu, and Anderson's 2014 paper titled "Integrating the ChE Curriculum via a Recurring Laboratory," which describes the benefits and importance of active learning to engineering education [15]. One common method of implementing active learning in Chemical Engineering is through laboratory courses that have projects that emphasize both theory and practice, which coincide with Feisel and Rosa's objectives of models and sensory awareness [15]. Feisel and Rosa's objectives of models and sensory awareness

are described and used as the reasoning for the selection of categories utilized in Chapters 6.2 and 6.5, respectively.

- Delluva, Salonga, Stewart, Arivalagan, Lehr, Dhurjati, and Shiflett's 2015 paper titled "ChE Junior Laboratory and the New Kinetics Experiment at the University of Delaware," which details the importance of the laboratory experience and improving the laboratory facilities through the continuous improvement of the projects centered around Feisel and Rosa's thirteen objectives [16]. The paper details the structure of the laboratory sequence, how continuous improvement of the projects is achieved, and the effect of continuous improvement on the laboratory experience. Five of Feisel and Rosa's thirteen objectives are discussed and used as the motives for categories used to categorize the assets in Chapter 6 [16].

The learning objectives in the undergraduate engineering courses can only be achieved if adequate laboratory facilities exist. General Criterion 7 from the ABET's criteria for accrediting engineering programs states: "Modern tools, equipment, computing resources, and laboratories appropriate to the program must be available, accessible, and systematically maintained and upgraded to enable students to attain the student outcomes and to support program needs" [17]. To satisfy this criteria, each engineering program must explicitly comment on the state of the laboratory facilities, maintenance practices and upgrade plans.

In addition to engineering education, the undergraduate teaching laboratory serves as a means for the continuing professional development of the faculty, as stated in the 1986 publication by the National Research Council [3]. "The faculty member who develops and continues to revise a laboratory course for engineering students will find this experience to be a learning one" [18]. Chapter 8 of this work discusses current faculty interests in assets for the Chemical Engineering Laboratory.

2.2 Current Needs for Information for the Departmental Discussion on the Role of the Chemical Engineering Laboratory in the Undergraduate Curriculum

At the beginning of AY 2016-17, the faculty in the Chemical Engineering Department engaged in a focused discussion on the current state and potential improvements of the undergraduate laboratory course sequence. The discussion started in response to recurring operational issues with experiments operated with the distributed control system (DeltaV), but the scope increased very rapidly to include learning objectives and student outcomes. In the course of these discussions several facts as well as needs for additional information quickly emerged:

- Fact: The basic format of the laboratory courses has stayed the same for more than 25 years and the undergraduate laboratory experience receives high praise by current students and alumni.
- Fact: Although the laboratory facilities and equipment have been regularly updated, a comprehensive long-term plan for the future of the laboratory does not exist, and most of the upgrades have been done on a short-term or ad hoc basis.
- Fact: The last comprehensive survey of teaching undergraduate laboratory courses in Chemical Engineering programs was published in 1978 [19].
- The demand for the development of new laboratory projects will most likely increase significantly in the short term, due primarily to the fact that five of the eleven faculty

members in the Chemical Engineering Department have been hired within the past 3 years.

- Need: Even though equipment is regularly moved in, out, and around the laboratory facilities, there are no up-to-date floor plans. The only way to examine space allocation is a physical walkthrough of the facilities.
- Need: Although it is recognized that different laboratory projects require and develop different skill sets, the specifics of these skill sets have not been defined and mapped to individual projects or to learning objectives.
- Need: Even though there are a significant number of different laboratory projects (19), the mix of subject areas covered by them has not been examined in recent history.
- Need: There is no formal system for tracking and documenting the utilization of the laboratory assets which constitute a significant investment.
- Need: The Chemical Engineering Department is committed to providing a balanced laboratory experience; however, no formal mapping or tracking has been done to ensure that each student develops a versatile skill set.

2.3 Project Goals

The purpose of this work is to fulfill the immediate need for information for the ongoing Departmental discussion on the future role of the Chemical Engineering Laboratory in the undergraduate courses. Specifically, the following needs are addressed:

- Deliver up-to-date floor plans of all laboratory facilities in an editable format so that future layout changes can be documented and tracked.
- Analyze current space allocation based on the delivered floor plans.

- Deliver an organized list of the assets in the Chemical Engineering Laboratory that are inventoried by the Institute.
- Deliver an organized list of only the assets used in the undergraduate laboratory courses.
- For the laboratory projects assigned in the undergraduate laboratory courses:
  - Define appropriate categories that relate to asset management.
  - Define appropriate categories that relate to the learning objectives presented by Feisel and Rosa [4].
  - Classify each project according to the defined categories.
  - Analyze the breakdown/distribution of projects according to the defined categories.
  - Define a systematic list of subject areas.
  - Determine the subject areas based on a detailed analysis of the theory and the operating procedures.
  - Analyze the breakdown of projects according to subject area.
  - Analyze project utilization during the last four academic years (AY 2013-14 to AY 2016-17).
  - Analyze the project breakdown for individual students' assignments during the last four academic years (AY 2013-14 to AY 2016-17).
- Interview all faculty in the Chemical Engineering Department and deliver a list of potential project additions or modifications based on faculty interests.
- Compare the Chemical Engineering Laboratory projects at Rose-Hulman to other institutions.

3. APPROACH AND METHOD

3.1 Floor Plans of Laboratory Facilities

Up-to-date floor plans will be rigorously documented utilizing a CAD program. These floor plans will include detailed dimensional drawings and layouts of the major laboratory assets, such as Experimental Setups, Analytical Instruments, and laboratory storage. Current space utilization will be determined based on the floor plans.

3.2 Inventory and Analysis of Current Assets with Respect to Asset Management

In the context of this project, “current” will refer to December 31, 2016. All assets in the Chemical Engineering Laboratory that are inventoried by the Institute or assigned as projects in the undergraduate laboratory courses will be considered major assets. The major assets will be subdivided into two categories:

- Experimental Setups – Assets that are used in projects assigned in the undergraduate laboratory courses.
- Analytical Instruments – Assets that are used for research or analytical support for undergraduate laboratory projects.

The breakdown of Experimental Setups and Analytical Instruments will be categorized according to:

- Number of Assets
- Footprint
- Purchase Cost

- Decade of Installation
- Experimental Scale

Additionally, the distribution of Experimental Setups will be further categorized according to:

- Footprint
- Purchase Cost

3.3 Categorization and Analysis of Experimental Setups with Respect to Learning Objectives

Feedback from the faculty and Chemical Engineering Department will be sought to define categories that relate the projects assigned in the undergraduate laboratory courses to learning objectives set forth by Feisel and Rosa [4]. The categories will be based on:

- Data Acquisition
- Subject Areas
- Origin
- Operational Control
- Degree of Automation

3.4 Analysis of Laboratory Project Assignments in the Undergraduate Laboratory Courses

The individual student project assignments in the undergraduate laboratory courses between AY 2013-14 and AY 2016-17 will be examined to determine:

- Experimental Setup Utilization
- Experimental Scale Breakdown

3.5 Faculty Interests in New Assets

Faculty members within the Chemical Engineering Department will be interviewed to document what Experimental Setups or Analytical Instruments they would like to see or implement in the Chemical Engineering Laboratory in the near future.

3.6 Comparison to Other Institutions

The assets in the Chemical Engineering Laboratory at Rose-Hulman will be compared to the assets available in the Chemical Engineering Laboratories of other institutions with similarities to Rose-Hulman, e.g., small undergraduate population, highly ranked, geographic proximity, etc. The focus will be on identifying:

- Experimental Setups at Rose-Hulman Institute of Technology with a Corresponding Equivalent at Surveyed Institutions
- Experimental Setups at Rose-Hulman Institute of Technology without a Corresponding Equivalent at Surveyed Institutions
- Experimental Setups at Surveyed Institutions without a Corresponding Equivalent at Rose-Hulman Institute of Technology

4. FLOOR PLANS AND SPACE ALLOCATION IN THE CHEMICAL ENGINEERING LABORATORY FACILITIES

4.1 Floor Plans

The Chemical Engineering Laboratory at Rose-Hulman occupies the ten separate laboratories listed in Table 4.1.1 The order in Table 4.1.1 is based on footprint, from the largest to the smallest. The current use of the space is summarized in the table as well. Current floor plans of the individual spaces are presented in Chapters 4.1.1 through 4.1.10 with a brief description.

For the purposes of legibility, the floor plans are presented at different scales. The reader is advised to compare footprints based on the dimensions indicated on the floor plans and not on the basis of the size of the CAD drawing.

Table 4.1.1 displays the ten separate laboratory spaces that compose the Chemical Engineering Laboratory at Rose-Hulman along with information related to the size (dimensions), area, and the current use of the laboratory spaces. Further analysis of the individual laboratory spaces is provided in the brief descriptions that accompany Chapters 4.1.1 through 4.1.10.

Table 4.1.1: Summary of Layouts (Ordered by Area)

Room	Size (L x W)	Area (ft^2)	Current Use
O-100 High Bay Laboratory	30 ft x 60 ft	1800	<u>Current Experimental Setups:</u> • Corning Column • Fluid Flow • Multipass Heat Exchanger • Reverse Osmosis • Tangential Flow Filtration • Tubular Reactor
O-102 Low Bay Laboratory	30 ft x 45 ft	1350	<u>Current Experimental Setups:</u> • Agitated Tank • Dryer • Filtration (Filter Press) • Fluidized Bed • Fuel Cell • Instrumentation and Control • Pumps <u>Analytical Instruments Associated with Experimental Setups:</u> • Microwave Dryer (Filtration (Filter Press))
O-226 Special Projects Laboratory	30 ft x 31 ft	930	<u>Current Experimental Setups:</u> • Saponification <u>Future Experimental Setups:</u> • Fermenter <u>Miscellaneous:</u> • Biochemical Engineering Research Equipment • Laboratory Glassware • Various Analytical Instruments

Table 4.1.1 Continued

Room	Size (L x W)	Area (ft^2)	Current Use
O-200B Instrument Laboratory	20 ft x 21 ft	420	Current Experimental Setups: • Drug Delivery Analytical Instruments Associated with Experimental Setups: • UV Spectrometer (Drug Delivery) Miscellaneous: • Laboratory Glassware • Various Analytical Instruments
O-204 Macromolecular Laboratory	16 ft x 26 ft	416	Analytical Instruments Associated with Experimental Setups: • Drop Shape Analyzer (Ultrafiltration) Miscellaneous: • Laboratory Glassware • Research Equipment • Various Analytical Instruments
O-202 Kinetics Laboratory	14 ft x 26 ft	364	Current Experimental Setups: • Parr Reactor • Ultrafiltration Miscellaneous: • Laboratory Glassware • Various Analytical Instruments
O-100A Process Control Laboratory	16 ft x 20 ft	320	Current Experimental Setups: • Cooling Tower Miscellaneous: • DeltaV Servers • Process Instrumentation Storage

Table 4.1.1 Continued

Room	Size (L x W)	Area (ft^2)	Current Use
O-100B Unit Operations Control Room	13 ft x 20 ft	260	Miscellaneous: • DeltaV Servers
O-102B Dry Instrument Laboratory	10 ft x 22 ft	220	Analytical Instruments Associated with Experimental Setups: • Forced Convection Oven (Dryer) Miscellaneous: • Various Analytical Instruments
O-102A Wet Instrument Laboratory	10 ft x 22 ft	220	Current Experimental Setups: • Othmer Still Analytical Instruments Associated with Experimental Setups: • Density Meter (Corning Column) • Density Meter (Othmer Still) Miscellaneous: • Laboratory Glassware • Various Analytical Instruments

4.1.1 High Bay Laboratory (O-100)

The High Bay Laboratory, which is shown in Figure 4.1.1.1, has dimensions of 30 ft by 60 ft, thereby yielding a total area of 1,800 ft^2. The High Bay Laboratory currently houses the following Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Corning Column
- Fluid Flow
- Multipass Heat Exchanger
- Reverse Osmosis
- Tangential Flow Filtration
- Tubular Reactor

Additionally, there is a safety shower and eyewash station located directly adjacent to the Tubular Reactor Experimental Setup.

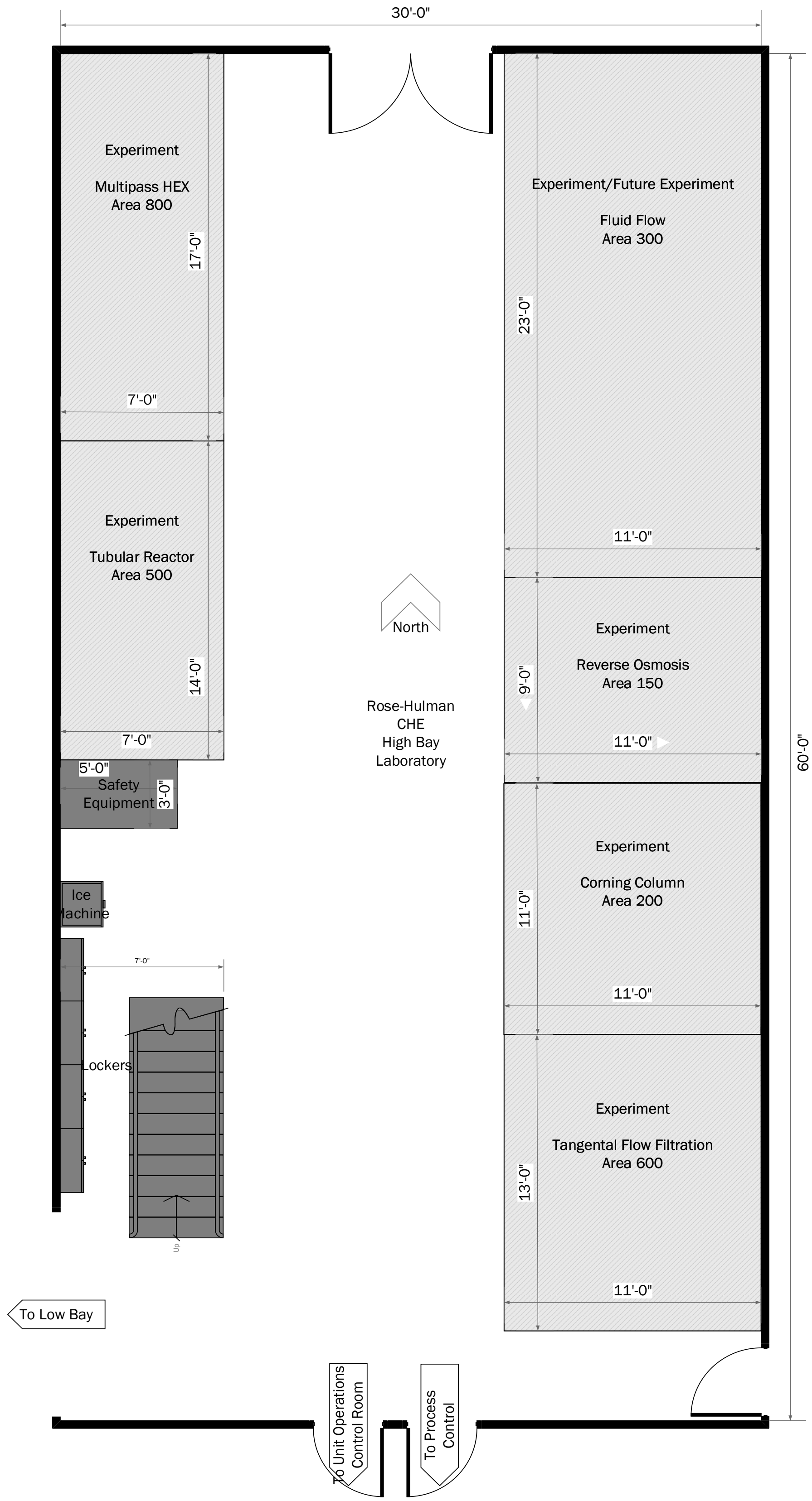

Figure 4.1.1.1: High Bay Laboratory (O-100) Floor Plan

4.1.2 Low Bay Laboratory (O-102)

The Low Bay Laboratory, which is shown in Figure 4.1.2.1, has dimensions of 30 ft by 45 ft, thereby yielding a total area of 1,350 ft^2. The Low Bay Laboratory currently houses the following Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Agitated Tank
- Filtration (Filter Press)
- Fluidized Bed
- Fuel Cell
- Instrumentation and Control
- Pumps
- Dryer

The Filtration (Filter Press) Experimental Setup has a microwave dryer that serves as an associated Analytical Instrument as well as a sink to facilitate greater ease in completing the standard operating procedure (SOP) while utilizing the Experimental Setup. Additionally, there is a safety shower and eyewash station located directly adjacent to the Pumps Experimental Setup.

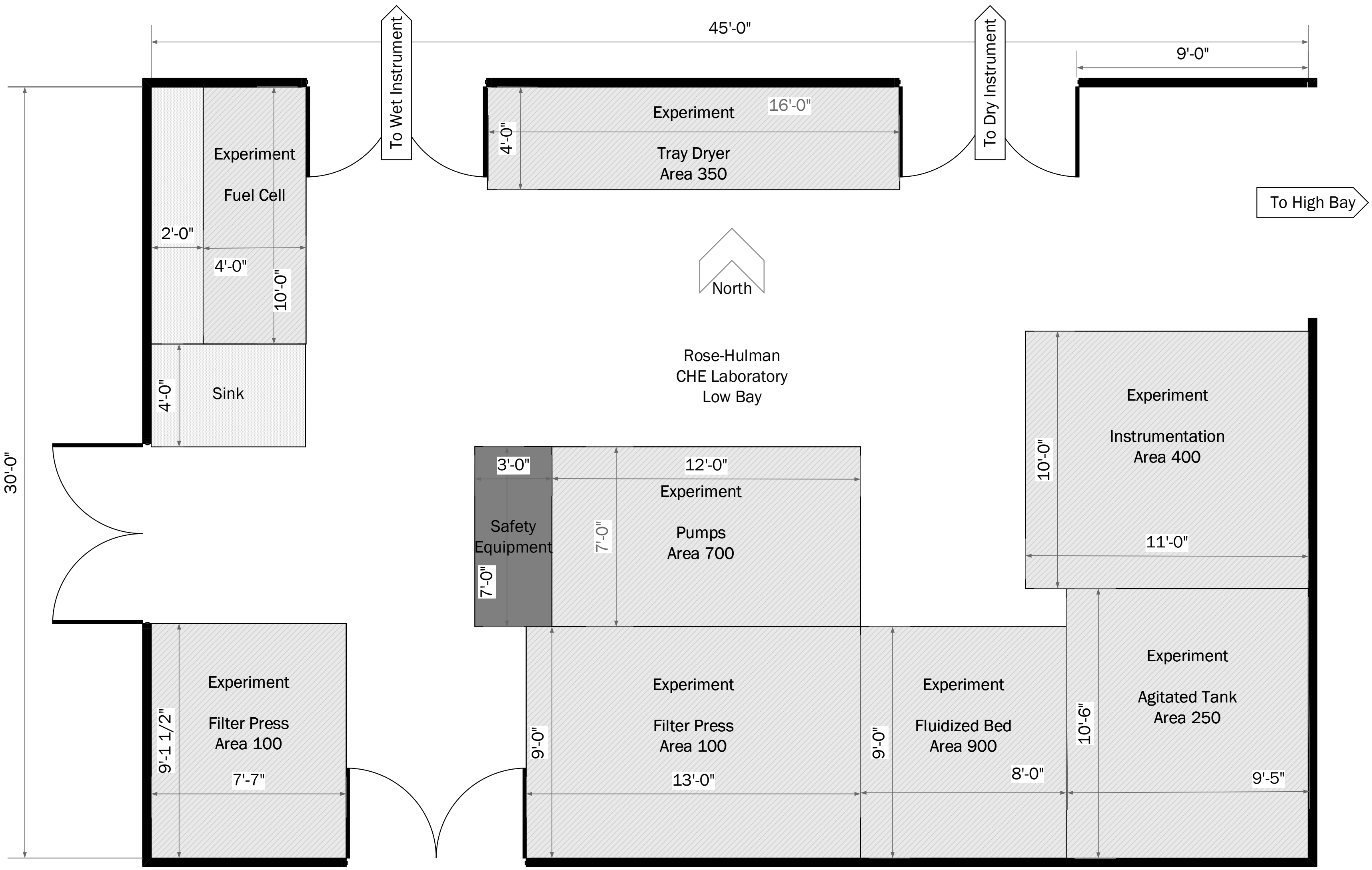

Figure 4.1.2.1: Low Bay Laboratory (O-102) Floor Plan

4.1.3 Special Projects Laboratory (O-226)

The Special Projects Laboratory, which is shown in Figure 4.1.3.1, has dimensions of 30 ft by 31 ft, thereby yielding a total area of 930 ft^2. The Special Projects Laboratory currently houses the following Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Fermenter (Future Experimental Setup)
- Saponification Reaction

The Saponification Reaction Experimental Setup has a laboratory hood as well as a sink to facilitate greater ease in completing the standard operating procedure (SOP) while utilizing the Experimental Setup. Additionally, there is a safety shower and eyewash station located on the back wall of the laboratory. Biochemical Engineering research equipment occupies the upper right corner of the laboratory. Currently, there are various Analytical Instruments, such as balances, pH meters, and a temperature bath, on the countertop space in the Special Projects Laboratory. There is also laboratory glassware and general laboratory storage in the cabinets both above and below the countertops. In addition to the laboratory hood associated with the Saponification Reaction Experimental Setup, there are two additional laboratory hoods located in the Special Projects Laboratory that are used for Introduction to Design (EM 103) and research projects/activities.

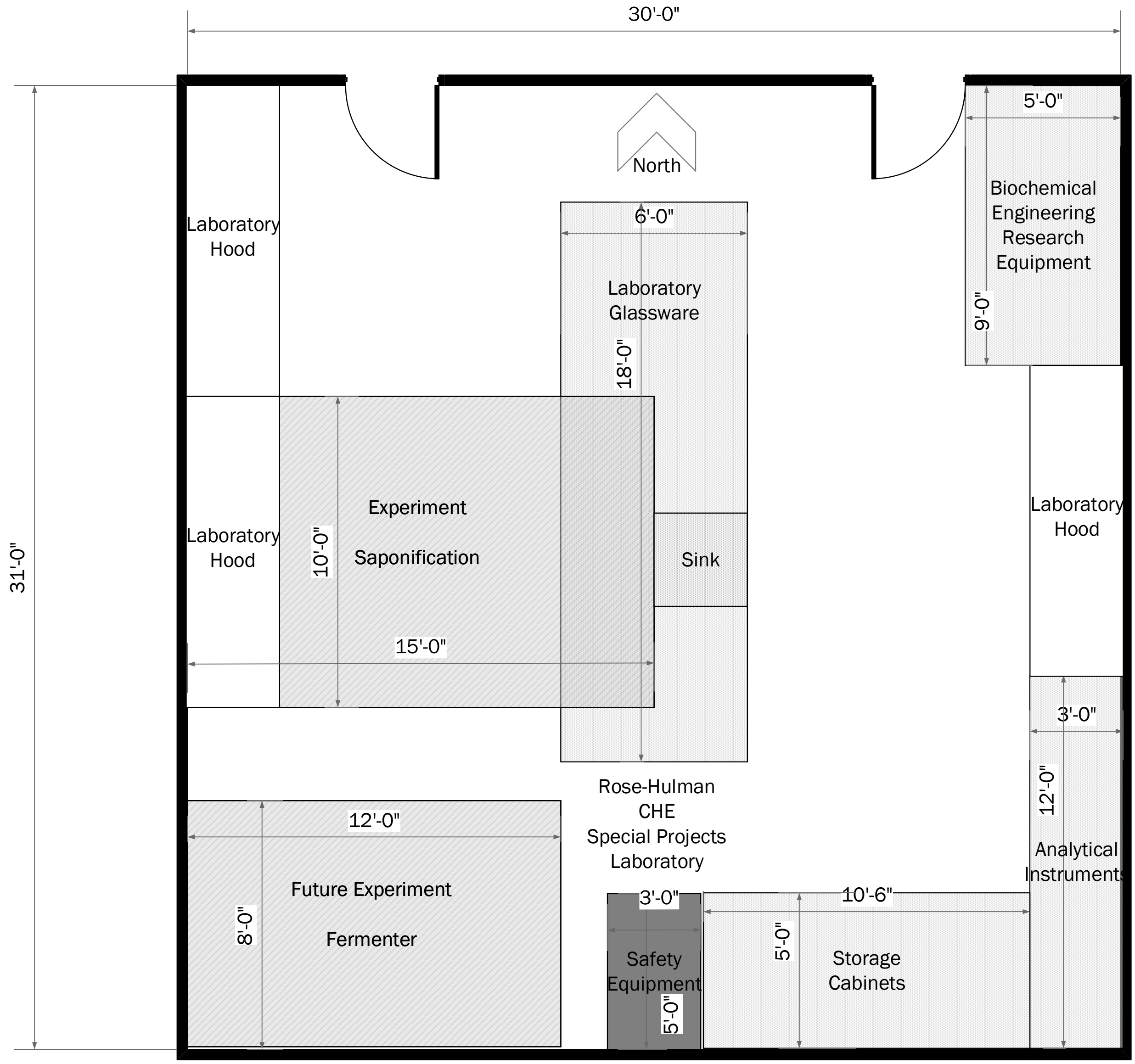

Figure 4.1.3.1: Special Projects Laboratory (O-226) Floor Plan

4.1.4 Instrument Laboratory (O-200B)

The Instrument Laboratory, which is shown in Figure 4.1.4.1, has dimensions of 20 ft by 21 ft, thereby yielding a total area of 420 ft^2. The Instrument Laboratory currently houses the following Experimental Setup used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Drug Delivery

The Drug Delivery Experimental Setup has a UV spectrometer that serves as an associated Analytical Instrument. Currently, there are various Analytical Instruments, such as an FTIR, a microscope, and a tensile test stretcher, on the countertop space in the Instrument Laboratory. There is also laboratory glassware and general laboratory storage in the cabinets both above and below the countertops as well as a laboratory hood that is used for research projects/activities.

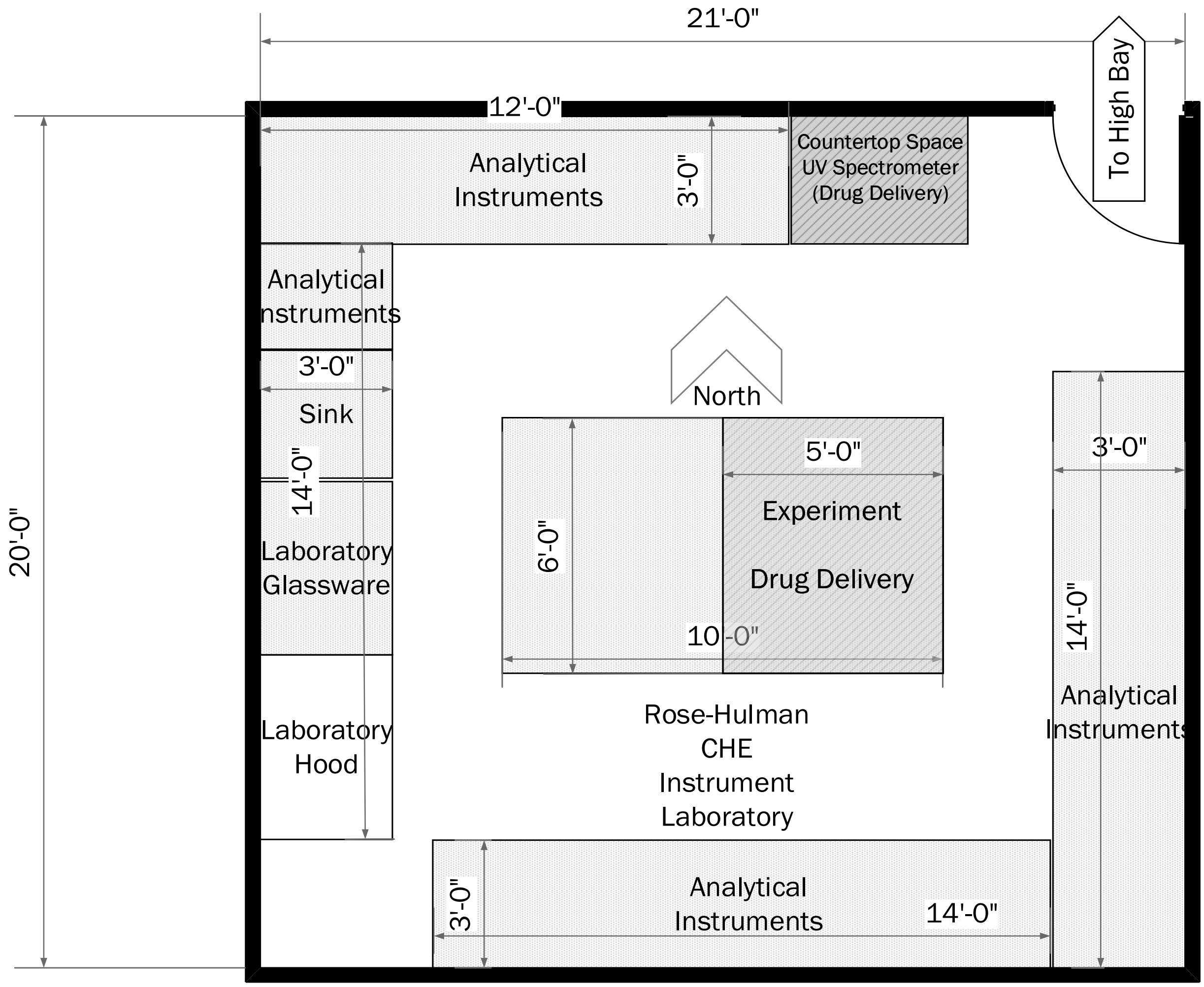

Figure 4.1.4.1: Instrument Laboratory (O-200B) Floor Plan

4.1.5 Macromolecular Laboratory (O-204)

The Macromolecular Laboratory, which is shown in Figure 4.1.5.1, has dimensions of 16 ft by 26 ft, thereby yielding a total area of 416 ft^2. The Macromolecular Laboratory does not currently house any Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413); however, the Ultrafiltration Experimental Setup, located in the Kinetics Laboratory, has a drop shape analyzer that serves as an associated Analytical Instrument. Research equipment occupies the central island of the laboratory. Currently, there are various Analytical Instruments, such as an inverted microscope and a temperature bath, on the countertop space in the Macromolecular Laboratory. There is also laboratory glassware and general laboratory storage in the cabinets both above and below the countertops as well as two laboratory hoods that are used for research projects/activities.

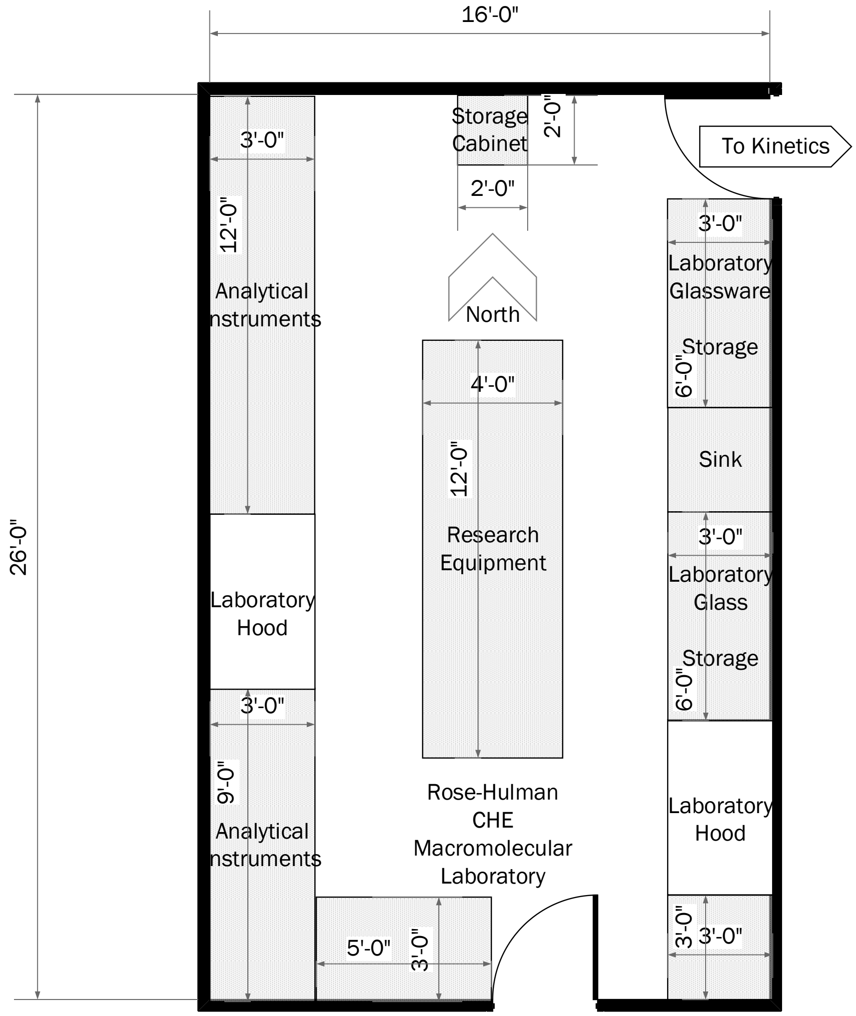

Figure 4.1.5.1: Macromolecular Laboratory (O-204) Floor Plan

4.1.6 Kinetics Laboratory (O-202)

The Kinetics Laboratory, which is shown in Figure 4.1.6.1, has dimensions of 14 ft by 26 ft, thereby yielding a total area of 364 ft^2. The Kinetics Laboratory currently houses the following Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Parr Reactor
- Ultrafiltration

The Parr Reactor Experimental Setup has a laboratory hood; additionally, there is a safety shower and eyewash station located towards the front wall of the laboratory. Currently, there are various Analytical Instruments, such as balances and pH meters, on the countertop space in the Kinetics Laboratory. There is also laboratory glassware and general laboratory storage in the cabinets both above and below the countertops.

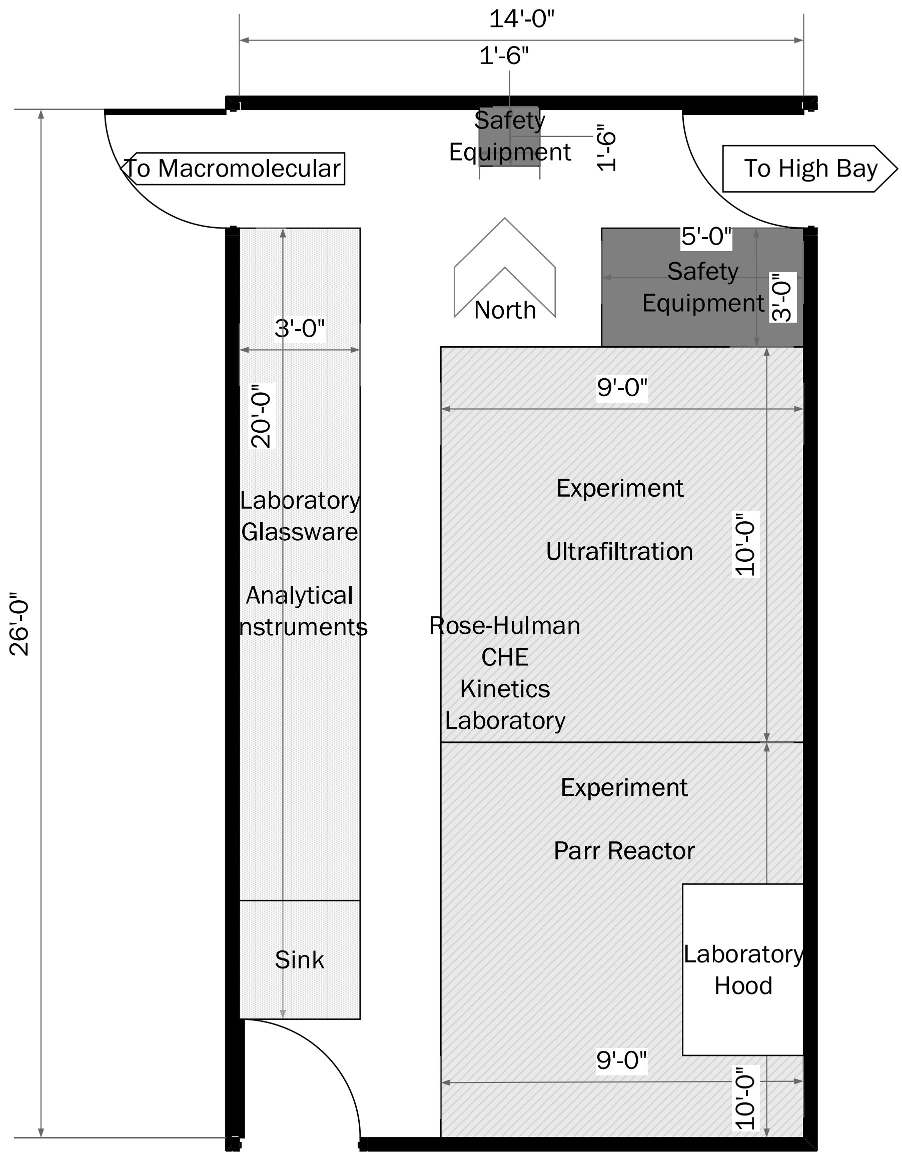

Figure 4.1.6.1: Kinetics Laboratory (O-202) Floor Plan

4.1.7 Process Control Laboratory (O-100A)

The Process Control Laboratory, which is shown in Figure 4.1.7.1, has dimensions of 16 ft by 20 ft, thereby yielding a total area of 320 ft^2. The Process Control Laboratory currently houses the following Experimental Setup used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Cooling Tower

DeltaV servers occupy the upper right corner of the laboratory. There is also process instrumentation storage in the cabinets both above and below the countertops.

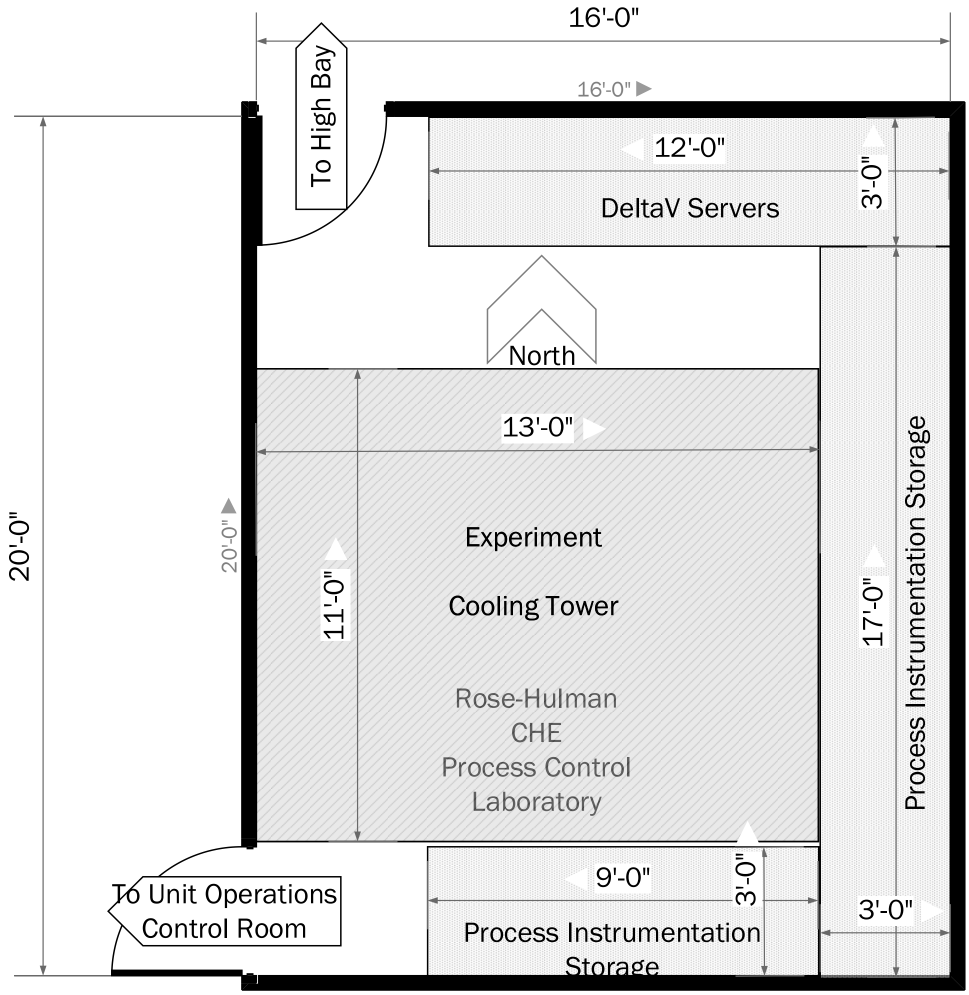

Figure 4.1.7.1: Process Control Laboratory (O-100A) Floor Plan

4.1.8 Unit Operations Control Room (O-100B)

The Unit Operations Control Room, which is shown in Figure 4.1.8.1, has dimensions of 13 ft by 20 ft, thereby yielding a total area of 260 ft^2. The Unit Operations Control Room does not currently house any Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413). DeltaV servers occupy the lower left corner of the laboratory.

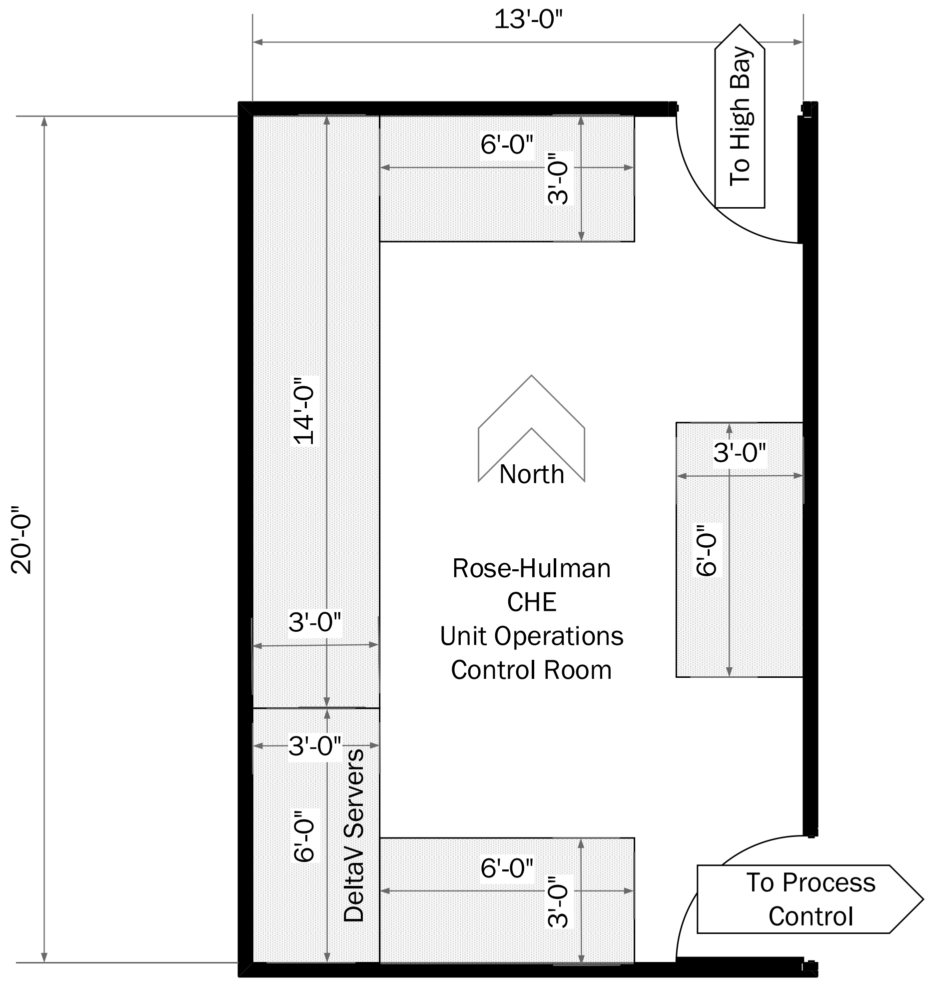

Figure 4.1.8.1: Unit Operations Control Room (O-100B) Floor Plan

4.1.9 Dry Instrument Laboratory (O-102B)

The Dry Instrument Laboratory, which is shown in Figure 4.1.9.1, has dimensions of 10 ft by 22 ft, thereby yielding a total area of 220 ft^2. The Dry Instrument Laboratory does not currently house any Experimental Setups used in the Chemical Engineering Laboratory sequence (CHE 411/412/413). The Dryer Experimental Setup, located in the Low Bay Laboratory, has a forced convection oven that serves as an associated Analytical Instrument. Currently, there are various Analytical Instruments, such as balances and a solids handling system, on the countertop space.

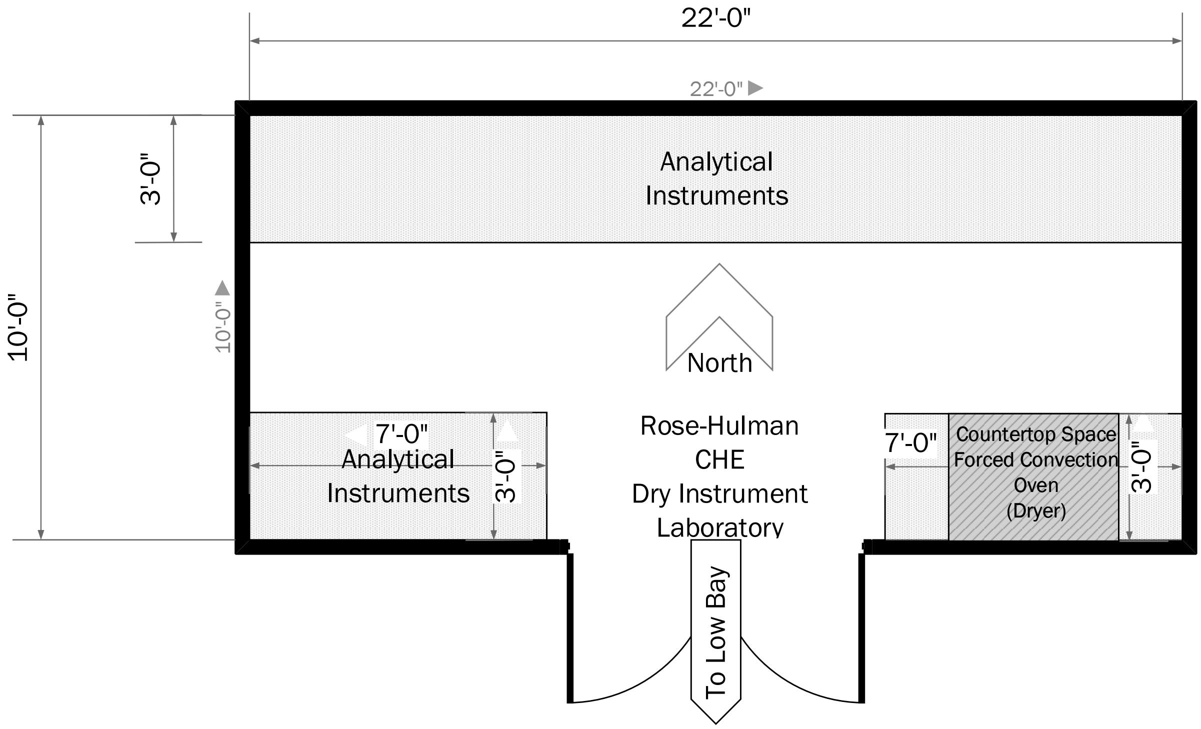

Figure 4.1.9.1: Dry Instrument Laboratory (O-102B) Floor Plan

4.1.10 Wet Instrument Laboratory (O-102A)

The Wet Instrument Laboratory, which is shown in Figure 4.1.10.1, has dimensions of 10 ft by 22 ft, thereby yielding a total area of 220 ft^2. The Wet Instrument Laboratory currently houses the following Experimental Setup used in the Chemical Engineering Laboratory sequence (CHE 411/412/413):

- Othmer Still

The Othmer Still Experimental Setup is located in a laboratory hood; furthermore, the Othmer Still Experimental Setup and the Corning Column Experimental Setup, located in the High Bay Laboratory, each have a density meter that serves as an associated Analytical Instrument. Currently, there are various Analytical Instruments, such as balances, a particle analyzer, and pH meters, on the countertop space.

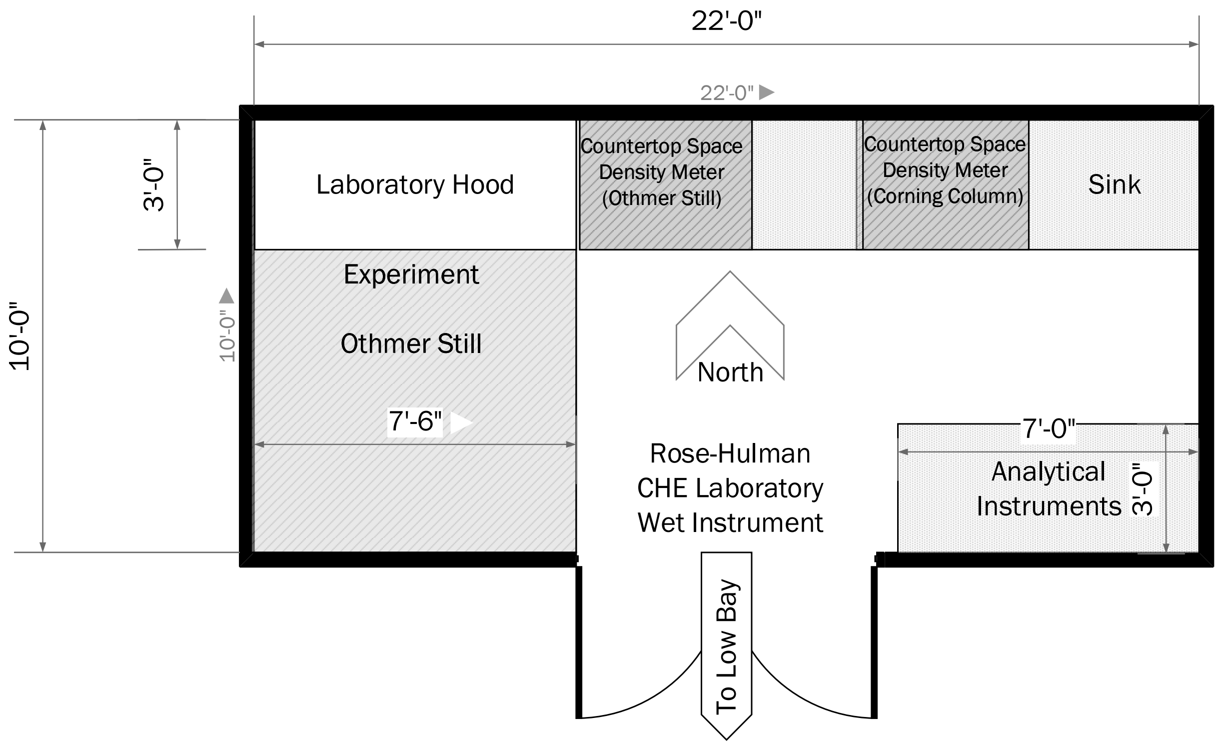

Figure 4.1.10.1: Wet Instrument Laboratory (O-102A) Floor Plan

4.2 Space Allocation Analysis

In the context of this work, the term "Space Allocation" refers to the spatial footprint of the assets on the laboratory floors and benchtops. Two metrics are defined to quantify Space Allocation:

- Laboratory Floor Density

$$Laboratory\ Floor\ Density = \frac{Occupied\ Floor\ Area}{Total\ Floor\ Area} \cdot 100\% \tag{1}$$

$$\begin{aligned} &Occupied\ Floor\ Area = \\ &Total\ Countertop\ Area + Floor\ Area\ With\ Permanently\ Installed\ Assets \\ &+ Floor\ Area\ With\ Portable\ Assets \end{aligned} \tag{2}$$

- Laboratory Countertop Density

$$\begin{aligned} &Laboratory\ Countertop\ Density \\ &= \frac{Occupied\ Countertop\ Area}{Total\ Countertop\ Area} \cdot 100\% \end{aligned} \tag{3}$$

$$\begin{aligned} &Occupied\ Countertop\ Area = \\ &Countertop\ Area\ With\ Permanently\ Installed\ Assets \\ &+ Countertop\ Area\ With\ Portable\ Assets \end{aligned} \tag{4}$$

4.2.1 Space Allocation of Laboratory Floor Space

The order in Table 4.2.1.1 is based on total floor area, from the largest to the smallest. Table 4.2.1.1 displays the total floor area, total countertop area, floor area with permanent installed assets, floor area with portable assets, and laboratory floor density of the ten separate laboratory spaces that compose the Chemical Engineering Laboratory at Rose-Hulman. The reader should note that the Process Control Laboratory (O-100A), Unit Operations Control Room (O-100B), and Dry Instrument Laboratory (O-102B) have a value of 0.0 ft^2 for the total countertop area based on the definition given later in this chapter; however, the tables and benchtops that occupy space in these laboratories are accounted for in all calculations.

Table 4.2.1.1: Space Allocation of Laboratory Floor Space (Ordered by Total Floor Area)

Laboratory	Total Floor Area (ft^2)	Total Countertop Area (ft^2)	Floor Area with Permanently Installed Assets (ft^2)	Floor Area with Portable Assets (ft^2)	Laboratory Floor Density
O-100	1800.0	0.0	833.0	0.0	46.28%
O-102	1350.0	20.0	619.1	40.0	50.30%
O-226	930.0	241.5	130.0	150.0	56.08%
O-200B	420.0	162.0	0.0	30.0	45.71%
O-204	416.0	175.0	0.0	0.0	42.07%
O-202	364.0	120.0	184.0	0.0	83.52%
O-100A	320.0	0.0	0.0	143.0	69.06%
O-100B	260.0	0.0	0.0	0.0	36.92%
O-102A	220.0	64.5	75.0	0.0	63.41%
O-102B	220.0	0.0	0.0	6.0	51.82%

Figure 4.2.1.1 is based on the data from Table 4.2.1.1 and presents the distribution of the total floor area on the primary axis and the floor area with permanently installed assets and the floor area with portable assets on the secondary axis of the individual laboratory spaces. Figure 4.2.1.1 and Table 4.2.1.1 show that the High Bay Laboratory (O-100) and the Low Bay Laboratory (O-102) have the greatest total floor areas, 1800 ft^2 and 1350 ft^2, respectively, and the greatest floor areas with permanently installed assets, 833 ft^2 and 619 ft^2, respectively. These data are consistent with the High Bay Laboratory and Low Bay Laboratory being the two primary teaching laboratories in the Undergraduate Laboratory courses; therefore, these laboratories contain the majority of the Experimental Setups that are fundamental to Undergraduate Laboratory courses as will be analyzed further in the coming chapters of this work.

Figure 4.2.1.2 is based on the data from Table 4.2.1.1 and presents the distribution of the laboratory floor density of the individual laboratory spaces in the Chemical Engineering Laboratory. Figure 4.2.1.2 and Table 4.2.1.1 show that each of the ten laboratories have a laboratory floor density greater than thirty-five percent (35%) with five of the ten laboratories having a laboratory floor density greater than fifty percent (50%). Laboratory floor density is a measure of how much of the available laboratory floor space is utilized in terms of space allocation. The Kinetics Laboratory (O-202) has the densest laboratory floor density (83.5%), which is consistent with the floor plan shown earlier in this chapter where two Experimental Setups and countertops occupy a majority of the available laboratory floor space. Conversely, the Unit Operations Control Room (O-100B) has the least dense laboratory floor density (36.9%) due to the fact that the Unit Operations Control Room contains no Experimental Setups or Analytical Instruments.

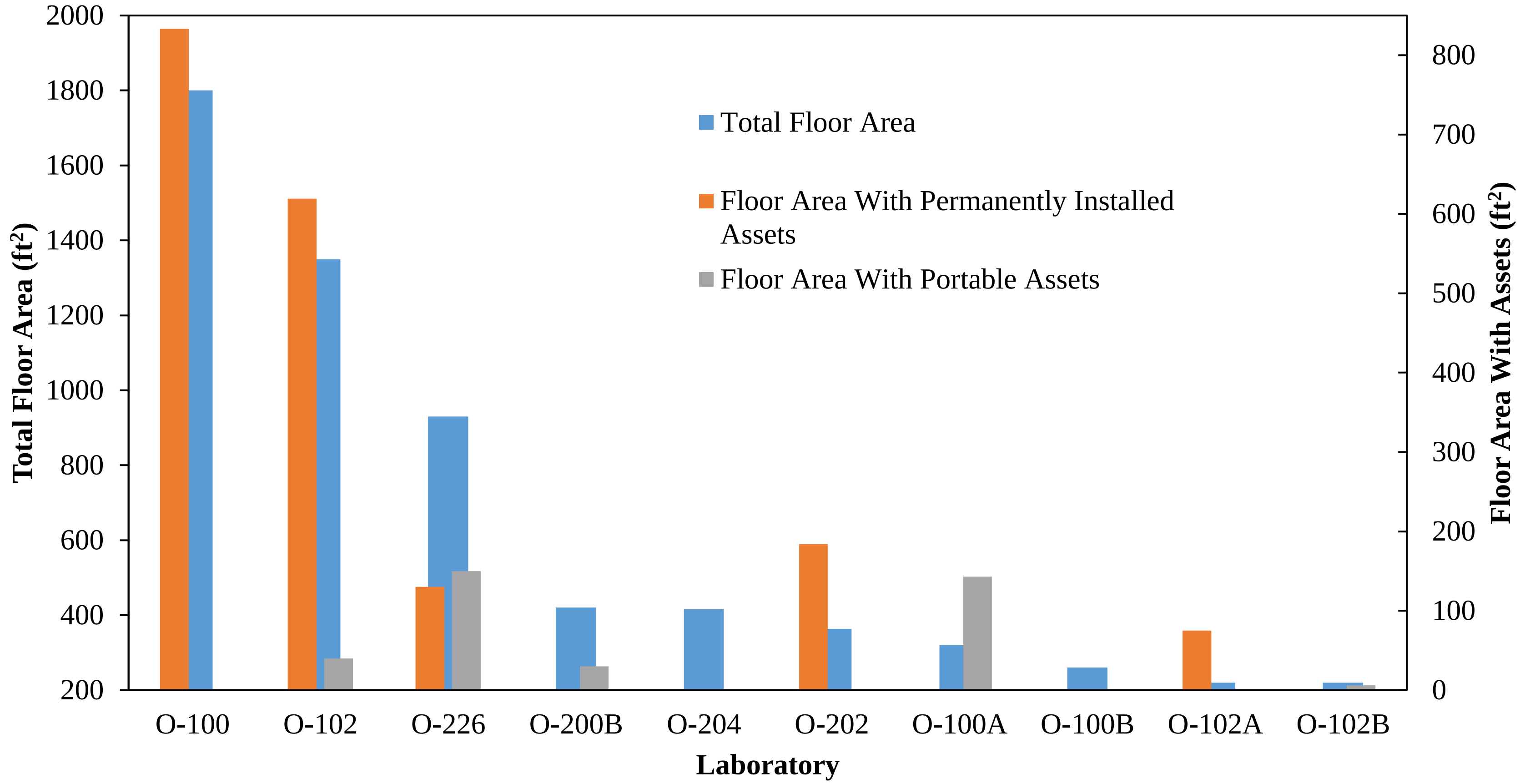

Figure 4.2.1.1: Space Allocation of Laboratory Floor Space (Ordered by Total Floor Area; Primary Axis – Total Floor Area; Secondary Axis – Floor Area with Permanently Installed Assets and Floor Area with Portable Assets)

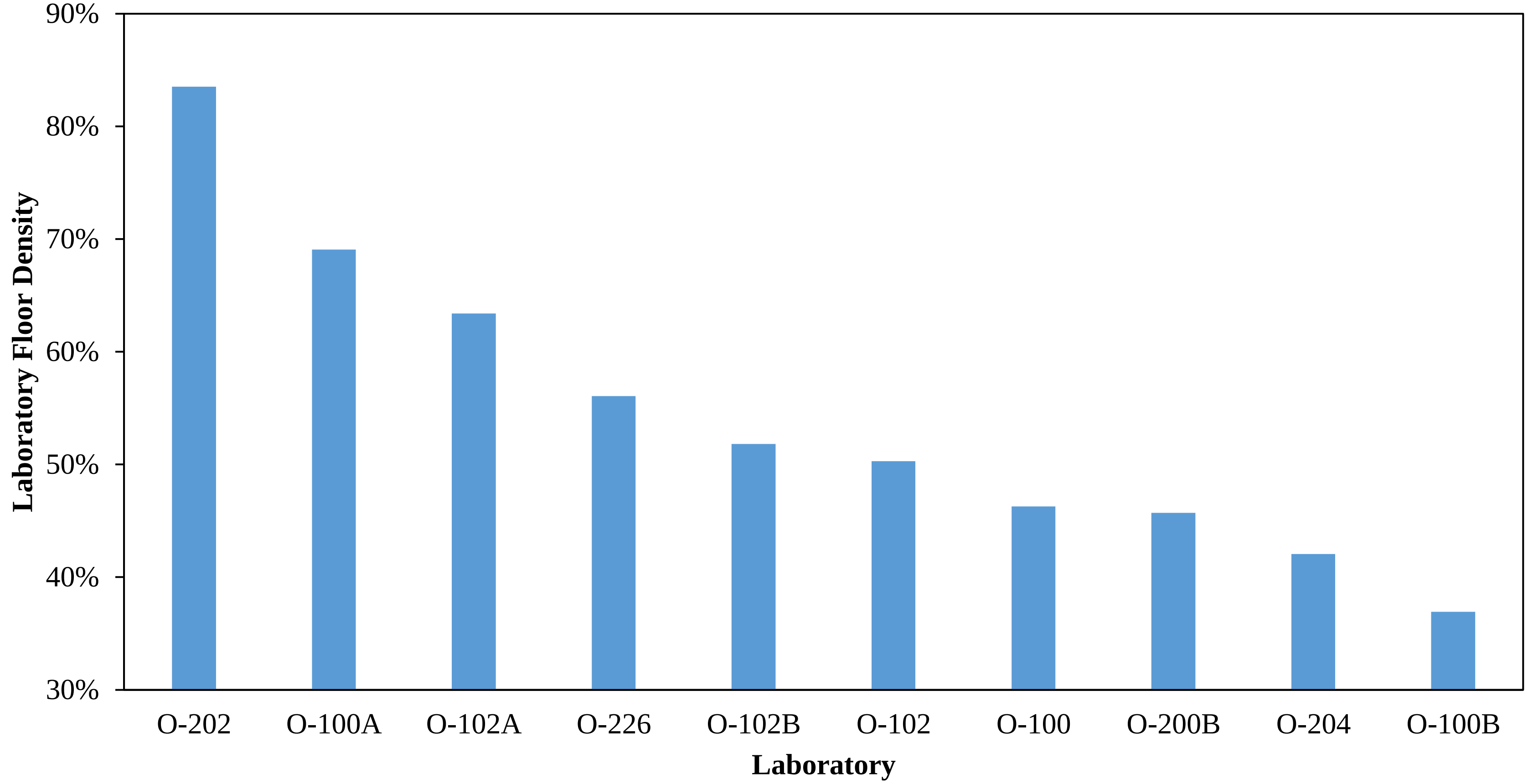

Figure 4.2.1.2: Laboratory Floor Density

4.2.2 Space Allocation of Laboratory Countertop Space

In the context of this work, “Countertop” is defined as countertop area with close proximity and access to laboratory utilities such as electricity, compressed air, water, and a sink. Laboratory countertop space is essential for providing work areas for projects. The total countertop area, countertop area with permanently installed assets, countertop area with portable assets, and countertop density for each laboratory is shown in Table 4.2.2.1. The laboratories are ordered based on total countertop area from the largest to the smallest.

There are four laboratories with no countertop space based on the definition provided above. Three of the laboratories, the Process Control Laboratory (O-100A), Unit Operations Control Room (O-100B), and Dry Instrument Laboratory (O-102B), do not have access to utilities while the fourth laboratory, the High Bay Laboratory (O-100) has access to utilities, but does not have available countertop space.

Table 4.2.2.1: Space Allocation of Laboratory Countertop Space (Ordered by Total Countertop Area)

Laboratory	Total Countertop Area (ft^2)	Countertop Area with Permanently Installed Assets (ft^2)	Countertop Area with Portable Assets (ft^2)	Laboratory Countertop Density
O-226	241.5	32.0	5.0	15.32%
O-204	175.0	0.0	3.0	1.71%
O-200B	162.0	50.5	32.0	50.93%
O-202	120.0	8.0	2.0	8.33%
O-102A	64.5	24.0	2.0	40.31%
O-102	20.0	0.0	0.0	0.00%
O-102B	0.0	N/A	N/A	N/A
O-100B	0.0	N/A	N/A	N/A
O-100A	0.0	N/A	N/A	N/A
O-100	0.0	N/A	N/A	N/A

Figure 4.2.2.1 is based on the data from Table 4.2.2.1 and presents the distribution of the total countertop area on the primary axis and the countertop area with permanently installed assets and the countertop area with portable assets on the secondary axis of the individual laboratory spaces in the Chemical Engineering Laboratory. The reader should note that the High Bay Laboratory (O-100), Process Control Laboratory (O-100A), Unit Operations Control Room (O-100B), and Dry Instrument Laboratory (O-102B) have been excluded from Figure 4.2.2.1 since the laboratories do not have any countertop area based on the definition provided earlier in this chapter. The reader should also note that the data were collected during the Winter Quarter since occupied countertop area is highly dependent upon when the data are collected; therefore, the countertop area with portable assets varies with what projects are being conducted in the Chemical Engineering Department. Figure 4.2.2.1 and Table 4.2.2.1 show that the Special Projects Laboratory (O-226) has the greatest total countertop area, 241.5 ft^2, which is consistent with the fact that in 2015, the laboratory was remodeled with the specific intent to increase countertop space. The occupied countertop area in the Special Projects Laboratory is intentionally kept low (37.0 ft^2) since the main purpose of this laboratory is to support small projects with a quick setup time and frequent turnover as is further evidenced in Figure 4.2.2.2.

Figure 4.2.2.2 is based on the data from Table 4.2.2.1 and presents the distribution of the laboratory countertop density of the individual laboratory spaces in the Chemical Engineering Laboratory. As noted previously, the High Bay Laboratory (O-100), Process Control Laboratory (O-100A), Unit Operations Control Room (O-100B), and Dry Instrument Laboratory (O-102B) do not have any countertop area based on the definition provided earlier in this chapter and have been excluded from Figure 4.2.2.1. The reader should again take note that the data were collected during the Winter Quarter since occupied countertop area is highly dependent upon when the data are collected; therefore, the laboratory countertop density varies with what projects are being conducted in the Chemical Engineering Department and laboratory benchtop density peaks during the Spring Quarter since Introduction to Design (EM 103) has many projects occurring simultaneously. Figure 4.2.2.1 and Table 4.2.2.1 show that four of the six laboratories that have countertop space have a laboratory countertop density less than thirty percent (30%), which is consistent with the fact that countertop space is typically used for smaller projects having a quick setup time and frequent turnover. The Instrument Laboratory (O-200B) and the Wet Instrument Laboratory (O-102A) have the greatest laboratory countertop densities, 50.9% and 40.3%, respectively, which is to be expected since the laboratories house many of the Analytical Instruments used by the entire Chemical Engineering Department.

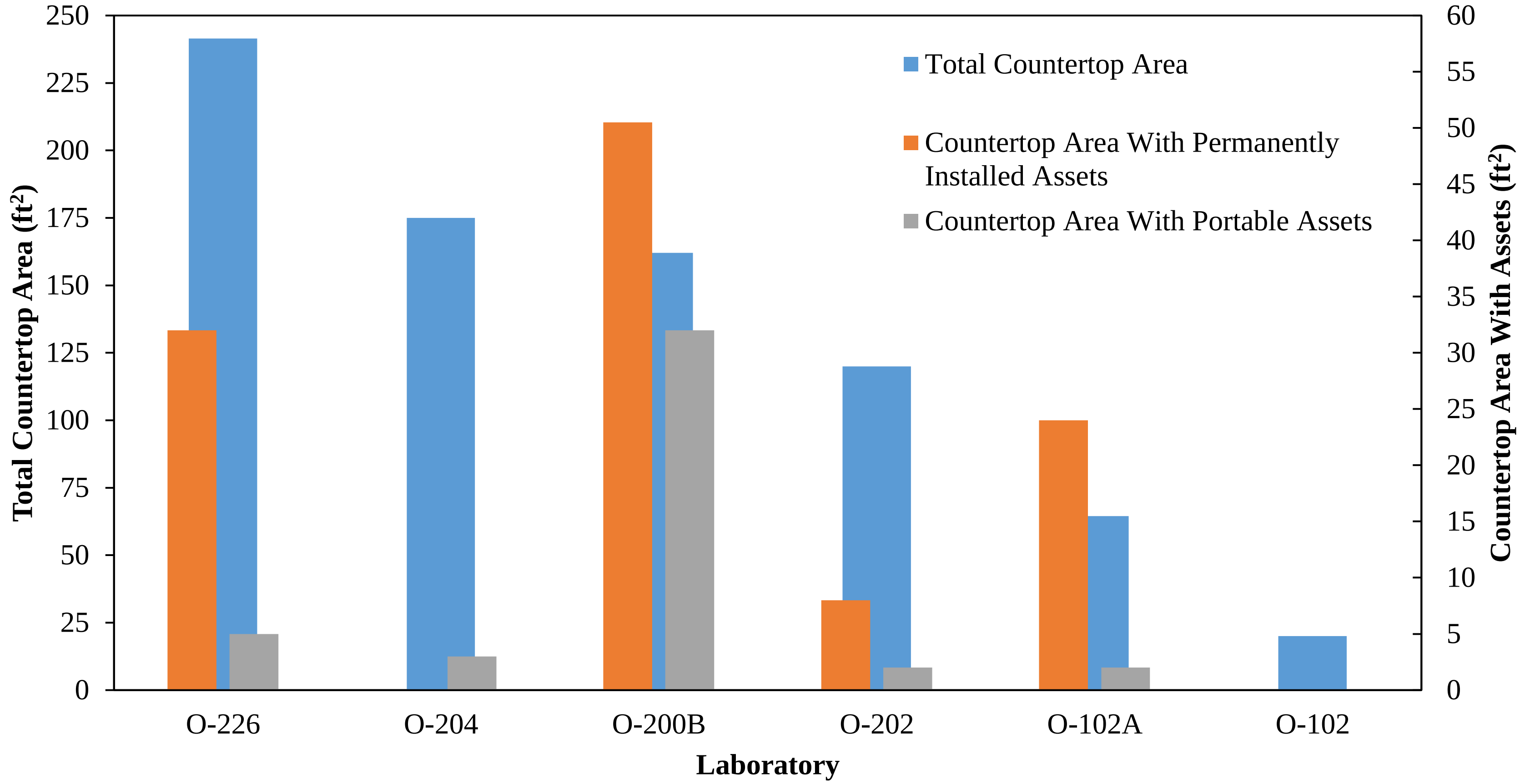

Figure 4.2.2.1: Space Allocation of Laboratory Countertop Space (Ordered by Total Countertop Area; Primary Axis – Total Countertop Area; Secondary Axis – Countertop Area with Permanently Installed Assets and Countertop Area with Portable Assets)

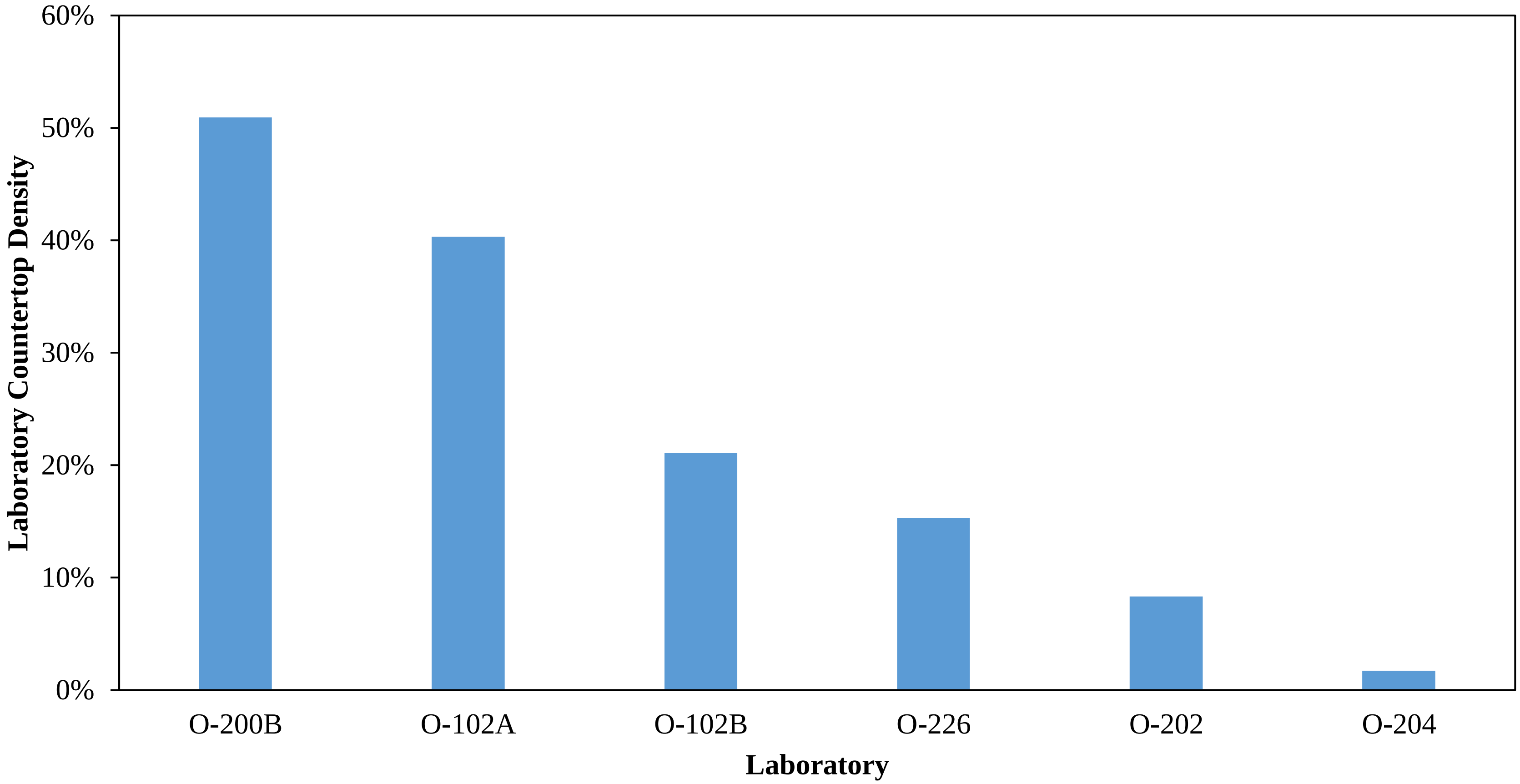

Figure 4.2.2.2: Laboratory Countertop Density

5. INVENTORY AND ANALYSIS OF CURRENT ASSETS IN THE CHEMICAL ENGINEERING LABORATORY WITH RESPECT TO ASSET MANAGEMENT

The purpose of this chapter is to inventory the major assets within the Chemical Engineering Laboratory and provide an analysis of those assets with respect to key categories related to asset management. The categories related to asset management include:

- Number of Assets
- Footprint
- Purchase Cost
- Decade of Installation
- Experimental Scale (Limited to Experimental Setups)

5.1 Breakdown of Experimental Setups and Analytical Instruments with Respect to the "Type" Category

The assets in the Chemical Engineering Laboratory must support undergraduate laboratory courses as well as research projects for faculty, undergraduate students, and graduate students. The category "Type" has been developed to determine whether an asset supports undergraduate laboratory courses or research. The assets in the Chemical Engineering Laboratory have been broken down into two groups:

- **"Experimental Setups"** – Assets that are assigned as projects in the Chemical Engineering Laboratory courses (CHE 411/412/413).

- **“Analytical Instruments”** – Assets that are not themselves projects in the Chemical Engineering Laboratory courses (CHE 411/412/413). Most of the Analytical Instruments are used for research; however, a small number are dedicated to supporting Experimental Setups.

The classification of the individual assets in the Chemical Engineering Laboratory according to the “Type” category is presented in Table A.1 in Appendix A. Other classifications that will be discussed later in this chapter are presented in Table A.1 as well. Table A.1 is separated into Experimental Setups first followed by Analytical Instruments, each of which is ordered by footprint, from largest to smallest.

Figure 5.1.1 is based on the data from Table A.1 and presents the breakdown of assets in the Chemical Engineering Laboratory by the “Type” category. The Experimental Setups, represent the minority, nineteen out of the sixty-seven, of the assets. Conversely, the Analytical Instruments represent the majority, forty-eight out of the sixty-seven, of the assets.

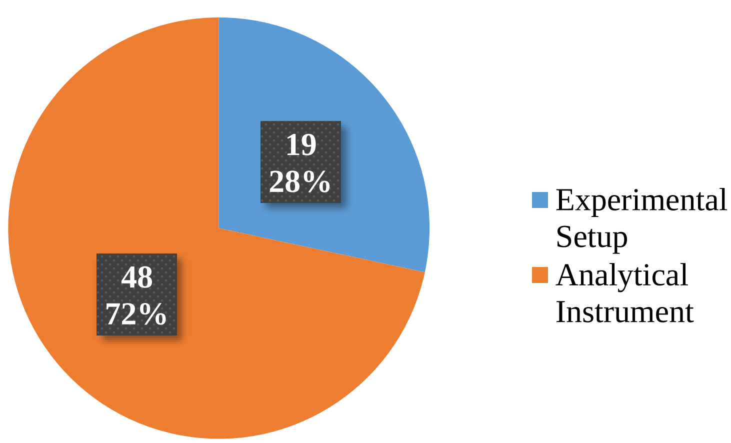

Figure 5.1.1: Asset Type Based on Number of Assets

<u>5.2 Breakdown of Experimental Setups and Analytical Instruments with Respect to Footprint</u>

Footprint is an important, and in many cases a limiting, factor in the deployment of assets in a laboratory environment. Understanding the footprint breakdown and distribution of the assets provides guidance for the addition of new assets and disposing of old assets. For this reason, the footprint of each asset in the Chemical Engineering Laboratory has been measured and recorded in Table A.1 in Appendix A.

Figure 5.2.1 is based on the data from Table A.1 and presents the breakdown of assets in the Chemical Engineering Laboratory by the "Footprint" category. Whereas Figure 5.1.1 communicates that the majority of assets are Analytical Instruments, Figure 5.2.1 shows that a large majority, or ninety-one percent (91%), of the total asset footprint is occupied by Experimental Setups. The reason for the disproportion between Figure 5.1.1 and Figure 5.2.1 is due to the scale of the assets. Most of the Experimental Setups are pilot scale units (see Chapter 5.5 for details). Pilot scale units typically have much larger footprints compared to Analytical Instruments, which are usually benchtop units.

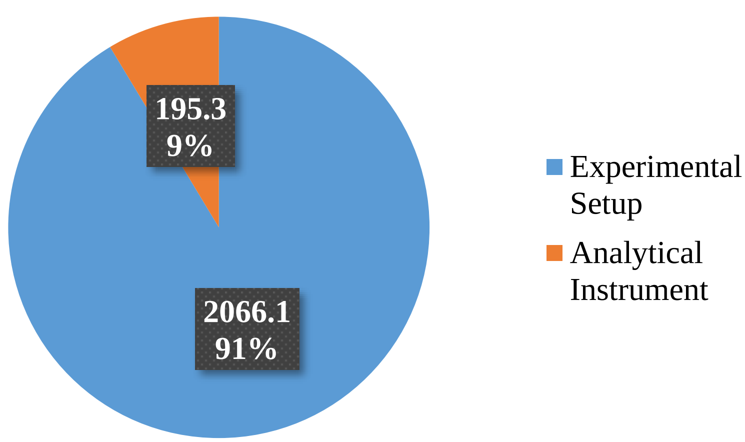

Figure 5.2.1: Asset Type Based on Footprint

5.2.1 Distribution of Experimental Setups with Respect to Footprint

Figure 5.2.1.1 is based on the data from Table A.1 and presents the distribution of Experimental Setups in the Chemical Engineering Laboratory by the "Footprint" category. Fluid Flow has the largest footprint (253 ft^2) in the Experimental Setup group. There are ten Experimental Setups with footprints between 75 ft^2 and 125 ft^2. Drug Delivery has the smallest footprint (25 ft^2) in the Experimental Setup group.

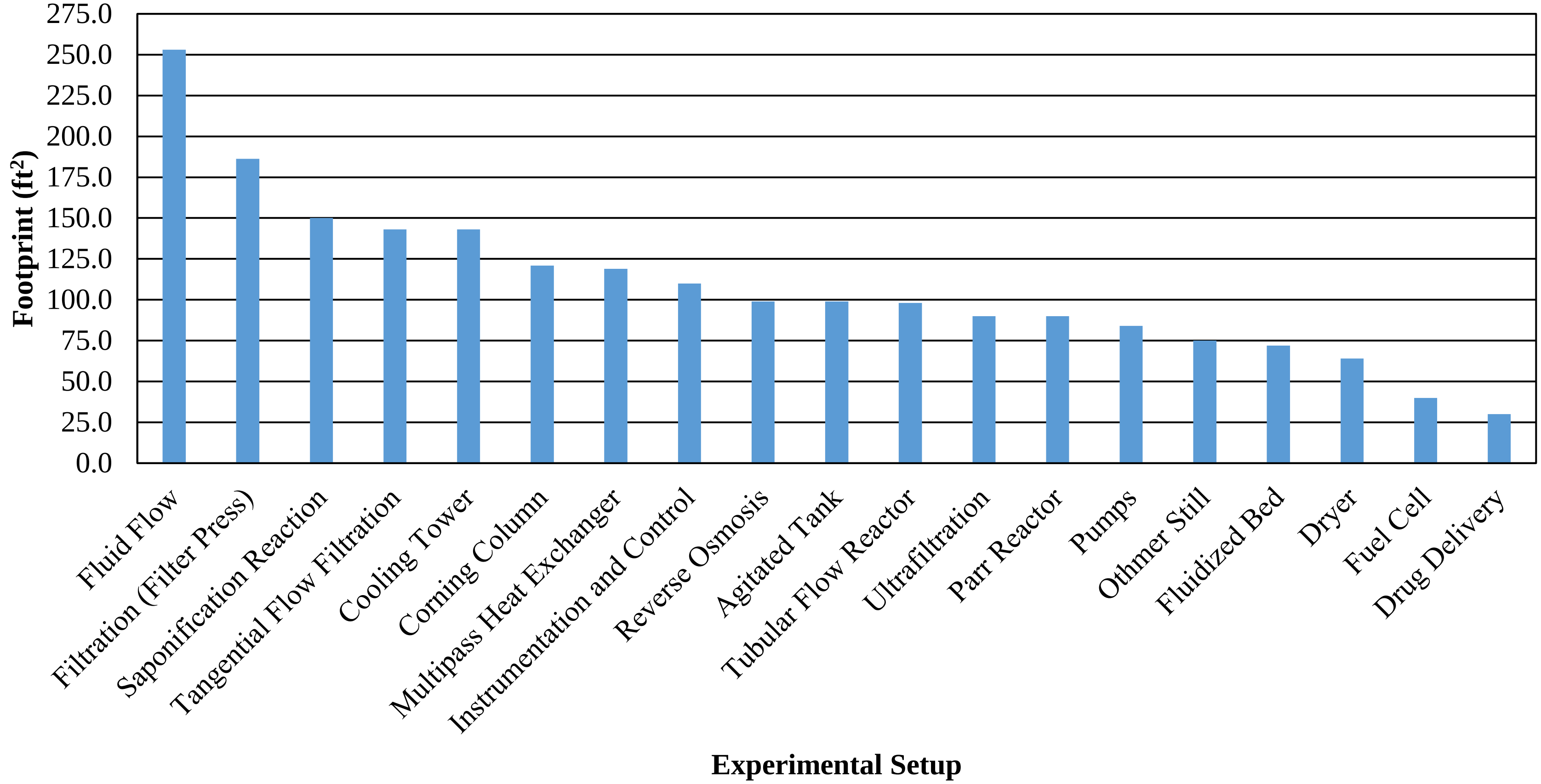

Figure 5.2.1.1: Footprint of Experimental Setups

5.3 Breakdown of Experimental Setups and Analytical Instruments with Respect to Purchase Cost

Purchase cost is an important, and very often, a limiting consideration for the addition of laboratory assets. Understanding the purchase cost structure of the existing assets provides guidance for future purchase decisions. For this reason, the purchase cost of each asset in the Chemical Engineering Laboratory has been reported in Table B.1 in Appendix B. Other information about the assets that will be discussed later in this work is presented in Table B.1 as well. In Table B.1, the Experimental Setups are listed first followed by the Analytical Instruments, with each subgroup ordered by purchase cost, from largest to smallest.

A majority of the purchase cost information in Table B.1 was obtained from the Dean's Current List of Equipment, which is an official Rose-Hulman Institute of Technology document. A copy of the Dean's Current List of Equipment used in this work can be found in Appendix C. For the remainder of the assets in the Chemical Engineering Laboratory, purchase cost information was not available in the Dean's Current List of Equipment. For these assets, the purchase cost was determined based on the Chemical Engineering Department purchase records. The source for the purchase cost information for each asset is given in Table B.1 in Appendix B.

The data from Table B.1 are shown in Figure 5.3.1, which presents the breakdown of assets in the Chemical Engineering Laboratory by the "Purchase Cost" category. Figure 5.3.1 shows that in total, just over $1,000,000.00 has been invested in assets within the Chemical Engineering Laboratory with a fairly balanced split, fifty-six percent (56%) to forty-four percent (44%), between Experimental Setups and Analytical Instruments.

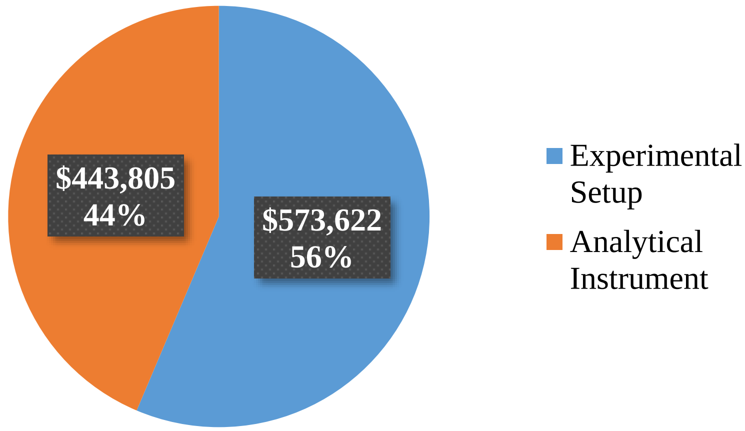

Figure 5.3.1: Asset Type Based on Purchase Cost

<u>5.3.1 Distribution of Experimental Setups with Respect to Purchase Cost</u>

The distribution of Experimental Setups in the Chemical Engineering Laboratory by the "Purchase Cost" category are shown in Figure 5.3.1.1 using data from Table B.1. The Corning Column has the highest purchase cost ($150,000.00). This Experimental Setup is the centerpiece of the Chemical Engineering Laboratory and represents an operation that is an iconic unit operation of Chemical Engineering. In general, fifteen (15) out of the nineteen (19) Experimental Setups have a purchase cost less than $30,000.00. The reader should take special notice of the second most expensive Experimental Setup in terms of purchase cost, the Tangential Flow Filtration Experimental Setup, as there is an interesting relationship between the purchase cost and utilization in CHE 411/412/413 that will be addressed later in this work.

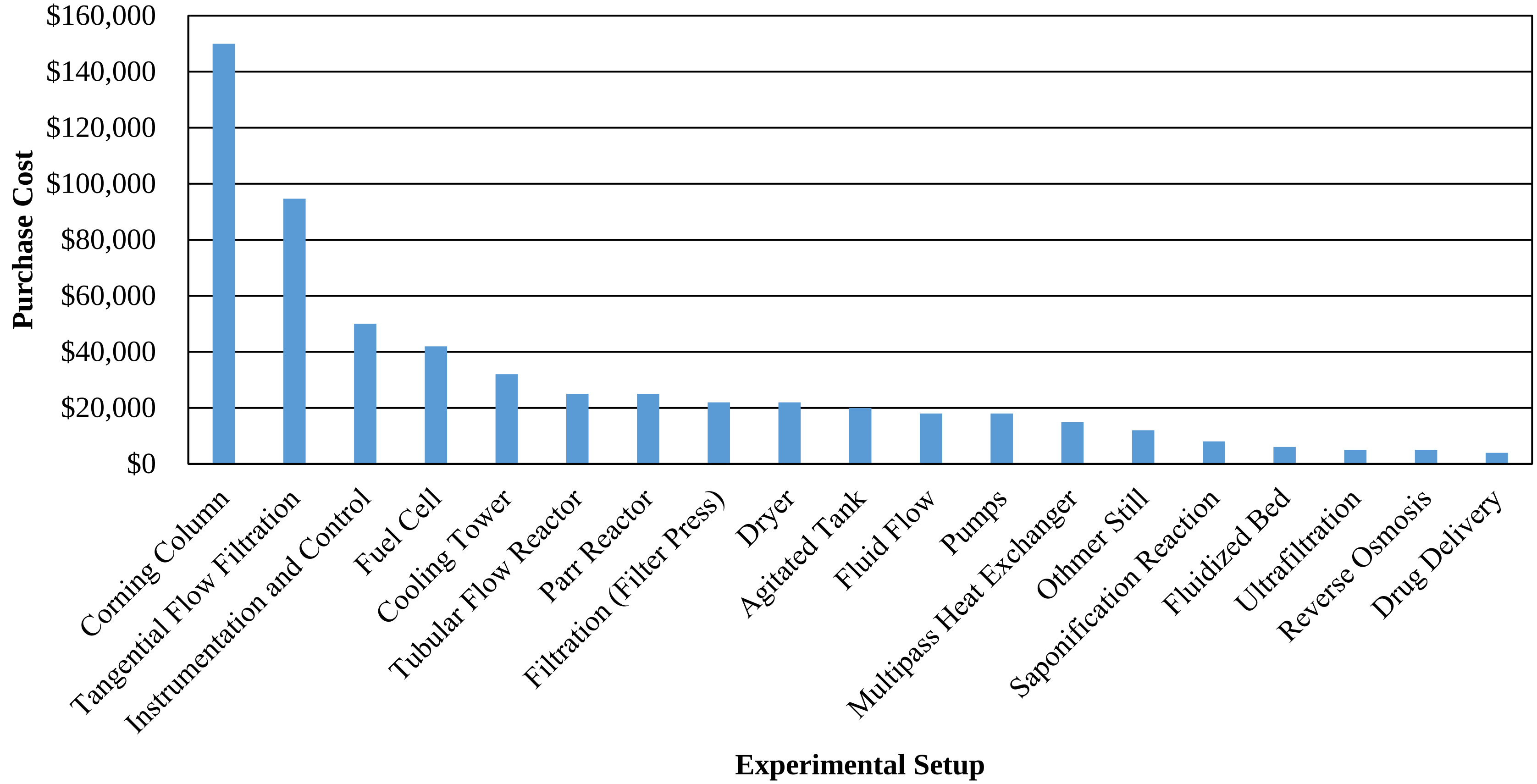

Figure 5.3.1.1: Purchase Cost of Experimental Setups

5.4 Breakdown of Experimental Setups and Analytical Instruments with Respect to Decade of Installation

The “Year of Installation” provides an additional dimension for the analysis of the assets in the Chemical Engineering Laboratory and is listed in Table B.1 in Appendix B. In the following chapter, the “Year of Installation” information was used to provide a breakdown of Experimental Setups and Analytical Instruments with respect to “Decade of Installation.”

5.4.1 Breakdown of Experimental Setups with Respect to Decade of Installation

Figure 5.4.1.1 is based on the data from Table A.1 and presents the breakdown of Experimental Setups in the Chemical Engineering Laboratory by the “Decade of Installation” category. A large portion, or approximately one-third, of the Experimental Setups have a decade of installation of the 1980s, which corresponds with the opening of the current Chemical Engineering Laboratory building in 1983. Wear and tear of the Experimental Setups and new technology have led to gradual replacement of the Experimental Setups. The largest portion, or approximately forty percent (40%), of the Experimental Setups have a decade of installation of the 2010s, which correlates with the increased undergraduate enrollment in the Chemical Engineering program at Rose-Hulman.

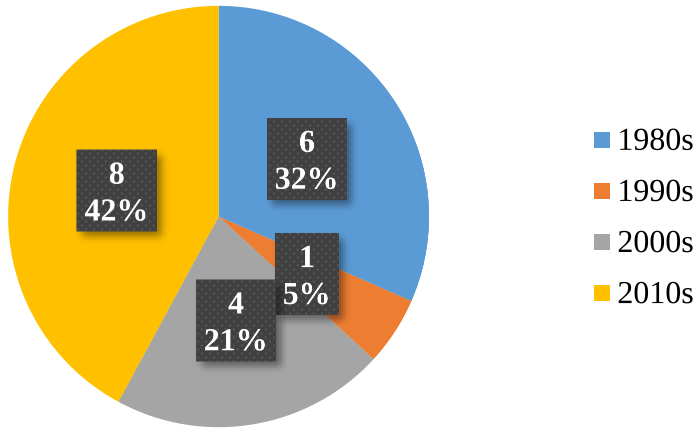

Figure 5.4.1.1: Decade of Installation of Experimental Setups

5.4.2 Breakdown of Analytical Instruments with Respect to Decade of Installation

Figure 5.4.2.1 is based on the data from Table A.1 and presents the breakdown of Analytical Instruments in the Chemical Engineering Laboratory by the "Decade of Installation" category. The largest portion, fifty percent (50%), of the Analytical Instruments have a decade of installation of the 2000s. Comparison between Figure 5.4.1 and Figure 5.4.2 reveals that during the 2000s, the Chemical Engineering Department prioritized the addition of Analytical Instruments as opposed to Experimental Setups; however, during the 2010s, the Chemical Engineering Department has prioritized the addition of Experimental Setups in order to accommodate the growth of undergraduate enrollment in the Chemical Engineering program at Rose-Hulman.

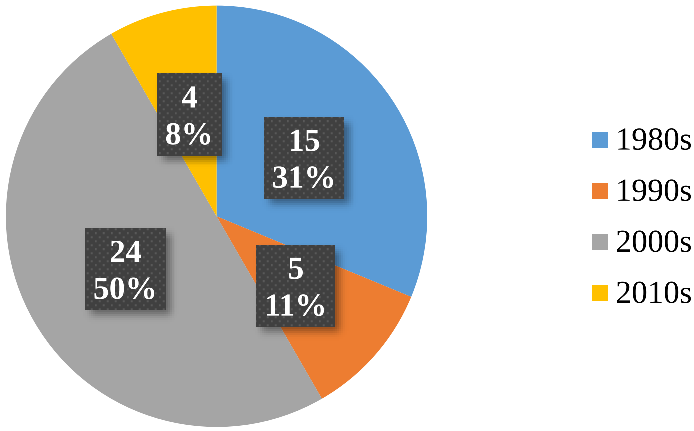

Figure 5.4.2.1: Decade of Installation of Analytical Instruments

5.5 Breakdown of Experimental Setups with Respect to Experimental Scale

The benefits of having both pilot scale and bench scale Experimental Setups in the Chemical Engineering Laboratory are outlined by Hesketh and Slater [20]. Pilot scale Experimental Setups give students a more realistic depiction of actual processing equipment; however, they are expensive, complex to operate, and require longer experimentation times [20]. Bench scale Experimental Setups are generally less expensive, less complex, require less time for experimentation, occupy less space, and can be easily relocated; however, bench scale Experimental Setups do not always convey the intricacies of actual industrial operations [20]. Consequently, both pilot scale and bench scale Experimental Setups should be present in a well-balanced Chemical Engineering Laboratory.

The purpose of the "Experimental Scale" category is to identify the mixture of pilot scale and bench scale Experimental Setups in the Chemical Engineering Laboratory. The following definitions are used:

- **"Pilot Scale"** – The Experimental Setup is self-supporting and sits on the laboratory floor.

- **"Bench Scale"** – The Experimental Setup sits on a laboratory bench or countertop.

The classification of the individual Experimental Setups in the Chemical Engineering Laboratory according to the "Experimental Scale" category is presented in Table A.1 in Appendix A.

Figure 5.5.1 is based on the data from Table A.1 and presents the breakdown of Experimental Setups in the Chemical Engineering Laboratory by the "Experimental Scale" category. The pilot scale Experimental Setups represent the majority, approximately two-thirds, of the Experimental Setups. To understand this apparent imbalance, Table 5.5.1 provides a breakdown of the number of pilot scale and bench scale Experimental Setups by the decade of installation. In the 1980s and 1990s, the majority of the commissioned Experimental Setups were pilot scale, which reflects the trends in laboratory development at the time. In the more recent decades, i.e., during the 2000s and 2010s, the Chemical Engineering Laboratory has seen an evenly distributed mixture of additions of both pilot scale and bench scale Experimental Setups.

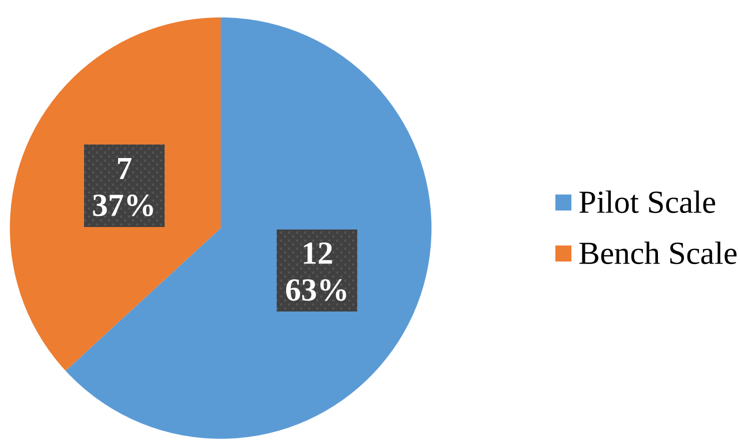

Figure 5.5.1: Experimental Scale of Experimental Setups

Table 5.5.1: Breakdown of Experimental Setups by Decade of Installation and Experimental Scale

Decade of Original Installation	Number of Pilot Scale Experimental Setups Installed	Number of Bench Scale Experimental Setups Installed
1980	5	1
1990	1	0
2000	2	2
2010	4	4

6. CATEGORIZATION AND ANALYSIS OF EXPERIMENTAL SETUPS WITH RESPECT TO LEARNING OBJECTIVES

The purpose of this chapter is to categorize the Experimental Setups within the Chemical Engineering Laboratory and provide an analysis of those Experimental Setups with respect to key categories that relate to learning objectives set forth by Feisel and Rosa [4]. The categories and the learning objectives that the categories relate to include:

- Data Acquisition – Instrumentation
- Subject Areas – Models
- Origin – Design
- Operational Control – Psychomotor
- Degree of Automation – Sensory Awareness

6.1 Breakdown of Experimental Setups with Respect to Data Acquisition

Data acquisition refers to the process of recording and archiving the information provided by measurement systems. Data acquisition is a required component of every experimental program. In their seminal paper, Feisel and Rosa place “[i]nstrumentation” as “[o]bjective 1” for instructional engineering laboratories [4]. Feisel and Rosa define the objective of instrumentation as “[a]pply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities,” which includes data acquisition [4]. Data acquisition systems can be as simple as a student logging a temperature readout in an experimental laboratory notebook or as complex as a networked computer system with remote access capabilities from virtually any place in the world. In this work, the data acquisition systems of the Experimental Setups in the Chemical Engineering Laboratory have been classified into four groups based on their level of sophistication:

- **"Local Displays without Historization"** – The instrument readings are displayed on local displays and the data are recorded manually in an experimental laboratory notebook or in a Microsoft Excel spreadsheet. This is the simplest data acquisition system. It has very low costs and maintenance associated with it. It offers operational convenience and an additional layer of safety because the local displays are installed in close proximity to the equipment and the operator can observe the equipment and the display at the same time. This type of data acquisition system provides satisfactory performance for gathering steady state data; however, the data cannot be retrieved after they have been displayed and the data acquisition process is prone to human data logging errors. It is very difficult, and most of the time impossible, to record readings for multiple experimental variables at the same instant in time. It is also very inconvenient to record dynamic data, especially in situations when more than one variable is tracked.
- **"Local Displays with Local Historization"** – This group is a subset of the turnkey Experimental Setups. In addition to being displayed on local displays, the instrument readings are recorded by a historization system integrated with the measurement instruments. This type of data acquisition system offers operational convenience and an added layer of safety due to the presence of local displays. Furthermore, local displays provide operational robustness since experiments can still be performed even if the local historian is non-operational. Local displays also reduce the risk of configuration errors in the historization system since they offer an independent verification for the values of the

recorded data. The presence of a local historian allows for data to be continuously recorded and stored, which is beneficial when collecting dynamic data and/or when it is necessary to collect data for multiple variables at the same instant in time. Additionally, this data acquisition system allows for data to be visualized immediately in charts on the local historian, which helps identify trends while the experiment is still ongoing. This data acquisition system also allows for data to be stored and retrieved. Because local historization is not standardized, each local historian has a separate learning curve associated with it. In addition, the communication between the local displays and the local historian can be difficult to configure. Another drawback of this data acquisition system is that the data cannot be retrieved remotely since they reside on local computers.

- **"DeltaV GUI with DeltaV Historian"** – The instrument readings are displayed on the DeltaV Graphical User Interface (GUI) and the data are recorded by the DeltaV Historian. The cost associated with this data acquisition system is low due to the absence of local displays on the field instruments. The DeltaV Historian allows for data to be continuously recorded and stored, which is beneficial when collecting dynamic data and/or when it is necessary to collect data for multiple variables at the same instant in time. Additionally, data are visualized immediately graphically on the DeltaV GUI, which helps to identify trends while the experiment is still ongoing. This data acquisition system also allows for data to be retrieved remotely since the data are stored on a networked server. Because the DeltaV data historization and retrieval process is standardized, students are able to develop portable skills that can be used on all Experimental Setups that utilize the DeltaV Historian. Due to the absence of local displays, this data acquisition system has a lower level of operational convenience and safety. Furthermore, this data acquisition system is prone to DeltaV configuration errors since the DeltaV GUI and the DeltaV Historian cannot be independently verified with readings from the local displays. The absence of local displays also reduces the operational robustness since the experiments cannot be performed if the DeltaV system is non-operational.

- **"Local Displays with DeltaV Historian"** – The instrument readings are displayed on local displays and the data are recorded by the DeltaV Historian. This data acquisition system offers operational convenience, an added layer of safety, and operational robustness due to the availability of local displays, as described earlier. The data can be retrieved remotely since they are stored on a networked server. Because the DeltaV data historization and retrieval process is standardized, students are able to develop portable skills that can be used on all Experimental Setups that utilize the DeltaV Historian.

The classification of the individual Experimental Setups in the Chemical Engineering Laboratory according to the "Data Acquisition" category is presented in Table 6.5.2 at the end of this chapter. Other classifications that will be discussed later in this chapter are presented in Table 6.5.2 as well. The Experimental Setups in Table 6.5.2 are ordered according to the level of complexity associated with the category of "Data Acquisition," and begin with the simplest group.

The breakdown of Experimental Setups in the Chemical Engineering Laboratory by the "Data Acquisition" category is shown in Figure 6.1.1 using data from Table 6.5.2. Almost all (eighteen out of the nineteen) Experimental Setups utilize local displays for operational convenience, operational robustness, and an added layer of safety. Data historization is implemented on fourteen out of the nineteen Experimental Setups; of those fourteen

Experimental Setups, ten utilize the DeltaV Historian platform and four utilize a local non-DeltaV historization platform. Only five out of the nineteen Experimental Setups lack data historization.

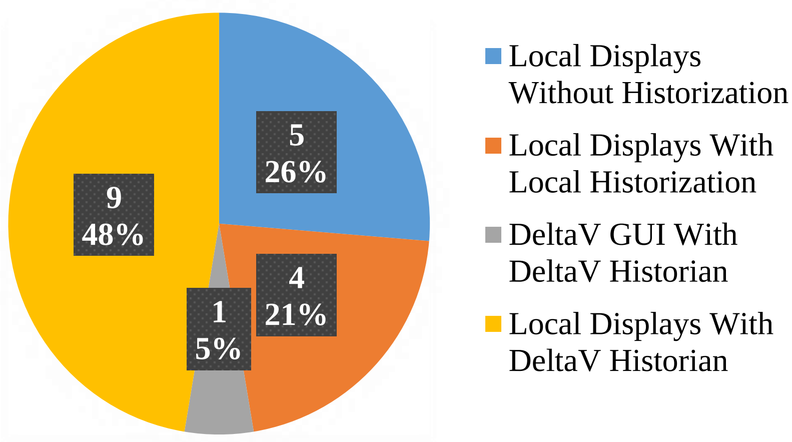

Figure 6.1.1: Data Acquisition of Experimental Setups

6.2 Breakdown of Experimental Setups with Respect to Primary Subject Area

A major foundation stone for the purpose of instructional engineering laboratories is the ability to relate theoretical concepts learned in the classroom to real-world problems. Feisel and Rosa list this as "[o]bjective 2" and call it "[m]odels" [4]. They define this objective as "[i]dentify the strengths and limitations of theoretical models as predictors of real-world behaviors" [4]. To effectively achieve this objective, the instructional engineering laboratories need to cover the subject areas taught in the curriculum.

A breakdown of the Experimental Setups in the Chemical Engineering Laboratory with respect to subject area is provided in Table 6.2.1. The subject areas are divided into two major groups: subject areas related to Unit Operations and subject areas related to core courses in the Chemical Engineering curriculum. The Unit Operations subject areas are defined based upon the classification provided in the Table of Contents of McCabe's, Smith's, and Harriott's *Unit Operations of Chemical Engineering* [21]. The core Chemical Engineering course subject areas are defined based on a review of the Chemical Engineering curriculum at Rose-Hulman.

Five different approaches were applied as the basis for assigning subject areas to individual Experimental Setups:

- **"First-Hand Experience"** – The subject areas were assigned based on first-hand experience obtained in CHE 411/412/413 and/or CHE 540.
- **"Review of CHE 411/412/413 Reports"** – The subject areas were assigned based on the review of student project reports written as part of CHE 411/412/413 (Chemical Engineering Laboratory Project I/II/III).
- **"Review of CHE 540 Reports"** – The subject areas were assigned based on the review of student project reports written as part of CHE 540 (Advanced Process Control).
- **"Review of Documentation"** – The subject areas were assigned based on the review of the materials available in the documentation portfolio for the Experimental Setup, such as Standard Operating Procedure (SOP) documents.
- **"Literature Review"** – The subject areas were assigned based on the review of relevant literature sources related to the Experimental Setup.

Each one of the first six Experimental Setups listed in Table 6.2.1 covers two subject areas. The remainder of the Experimental Setups are mapped to a single subject area. The specific rationale for the subject area assignments is given in Table 6.2.2.

Table 6.2.1: Subject Area Classifications of Experimental Setups

Experimental Setup	Subject Area Classification							Number of Subject Areas Covered	Basis for Classification
	McCabe, Smith, and Harriott [21]				Core CHE Courses				
	Fluid Mechanics	Heat Transfer	Mass Transfer	Particulate Solids	Thermo-dynamics	Kinetics	Process Control		
Tubular Flow Reactor						x	x	2	First-Hand Experience
Instrumentation and Control	x						x	2	First-Hand Experience
Fuel Cell			x			x		2	Review of Literature [22]
Dryer		x	x					2	Review of Documentation
Cooling Tower		x	x					2	Review of Documentation
Corning Column			x					1	Review of CHE 411/412/413 Reports
Ultrafiltration				x				1	Review of Documentation
Tangential Flow Filtration				x				1	Review of CHE 540 Reports

Table 6.2.1 Continued

Experimental Setup	Subject Area Classification							Number of Subject Areas Covered	Basis for Classification
	McCabe, Smith, and Harriott [21]				Core CHE Courses				
	Fluid Mechanics	Heat Transfer	Mass Transfer	Particulate Solids	Thermo-dynamics	Kinetics	Process Control		
Saponification Reaction						x		1	Review of Literature [23]
Reverse Osmosis			x					1	Review of Documentation
Pumps	x							1	First-Hand Experience
Parr Reactor						x		1	Review of Documentation
Othmer Still					x			1	First-Hand Experience
Multipass Heat Exchanger		x						1	Review of CHE 411/412/413 Reports
Fluidized Bed	x							1	Review of Documentation
Fluid Flow	x							1	Review of Documentation
Filtration (Filter Press)				x				1	First-Hand Experience

Table 6.2.1 Continued

Experimental Setup	**Subject Area Classification**							**Number of Subject Areas Covered**	**Basis for Classification**
	McCabe, Smith, and Harriott [21]				Core CHE Courses				
	Fluid Mechanics	Heat Transfer	Mass Transfer	Particulate Solids	Thermo-dynamics	Kinetics	Process Control		
Drug Delivery			x					1	Review of Literature [24]
Agitated Tank		x						1	Review of Documentation
Subject Area Total	4	4	6	3	1	4	2		

Table 6.2.2: Justification for Subject Area Classifications of Experimental Setups

Experimental Setup	Subject Areas	Rationale for Classification
Tubular Flow Reactor	Kinetics	Allows Students to Calculate the Conversion of a Chemical Reaction
	Process Control	Allows Students to Tune Coupled PID Control Loops
Instrumentation and Control	Fluid Mechanics	Allows Students to Obtain Pump Characteristics
	Process Control	Allows Students to Investigate Equipment Commonly Used in Process Control Applications Also Allows Students to Tune PID Controllers
Fuel Cell	Mass Transfer	Allows Students to Investigate Mass Transfer Limitations [22]
	Kinetics	Allows Students to Investigate Kinetic Limitations [22]
Dryer	Heat Transfer	Drying Is a Unit Operation where Heat and Mass Transfer Occur Simultaneously [21]
	Mass Transfer	
Cooling Tower	Heat Transfer	Heat and Mass Transfer Occur Simultaneously in Cooling Towers [21]
	Mass Transfer	
Corning Column	Mass Transfer	Distillation Is Classified as a Mass Transfer Unit Operation [21]
Ultrafiltration	Particulate Solids	Ultrafiltration Is Classified as a Unit Operation Involving Particulate Solids [21]
Tangential Flow Filtration	Particulate Solids	Tangential Flow Filtration Is Classified as a Unit Operation Involving Particulate Solids [21]

Table 6.2.2 Continued

Experimental Setup	Subject Areas	Rationale for Classification
Saponification Reaction	Kinetics	Allows Students to Obtain Reaction Rate Kinetic Parameters [23]
Reverse Osmosis	Mass Transfer	Reverse Osmosis Is Classified as a Mass Transfer Unit Operation [21]
Pumps	Fluid Mechanics	Allows Students to Obtain Pump Characteristics
Parr Reactor	Kinetics	Allows Students to Obtain Reaction Rate Data
Othmer Still	Thermodynamics	Allows Students to Collect and Analyze Vapor-Liquid Equilibrium Data
Multipass Heat Exchanger	Heat Transfer	Allows Students to Obtain Heat Transfer Coefficients for a Shell-and-Tube Heat Exchanger [21]
Fluidized Bed	Fluid Mechanics	Fluidized Beds Are Classified as a Fluid Mechanics Unit Operation [21]
Fluid Flow	Fluid Mechanics	Allows Students to Measure and Analyze Pressure Drop in Pipes and Fittings [21]
Filtration (Filter Press)	Particulate Solids	Cake Filtration Is Classified as a Unit Operation Involving Particulate Solids [21]
Drug Delivery	Mass Transfer	Allows Students to Collect and Analyze Diffusion Rate Data [24]
Agitated Tank	Heat Transfer	Allows Students to Obtain Heat Transfer Coefficients [21]

Figure 6.2.1 is based on the data from Table 6.2.1 and presents the breakdown of Experimental Setups in the Chemical Engineering Laboratory by the “Subject Areas” category. The most represented subject area is mass transfer, which is covered by six Experimental Setups. Following mass transfer, the subject areas of heat transfer, fluid mechanics, and kinetics are each covered in four Experimental Setups. The least represented subject area is thermodynamics with only one Experimental Setup. The core Chemical Engineering competencies of transport processes (fluid mechanics, heat transfer, and mass transfer) and kinetics are very well represented with fourteen and four Experimental Setups, respectively. The process control subject area seems underrepresented with only two Experimental Setups, especially given the fact that nine Experimental Setups are operated with automatic control.

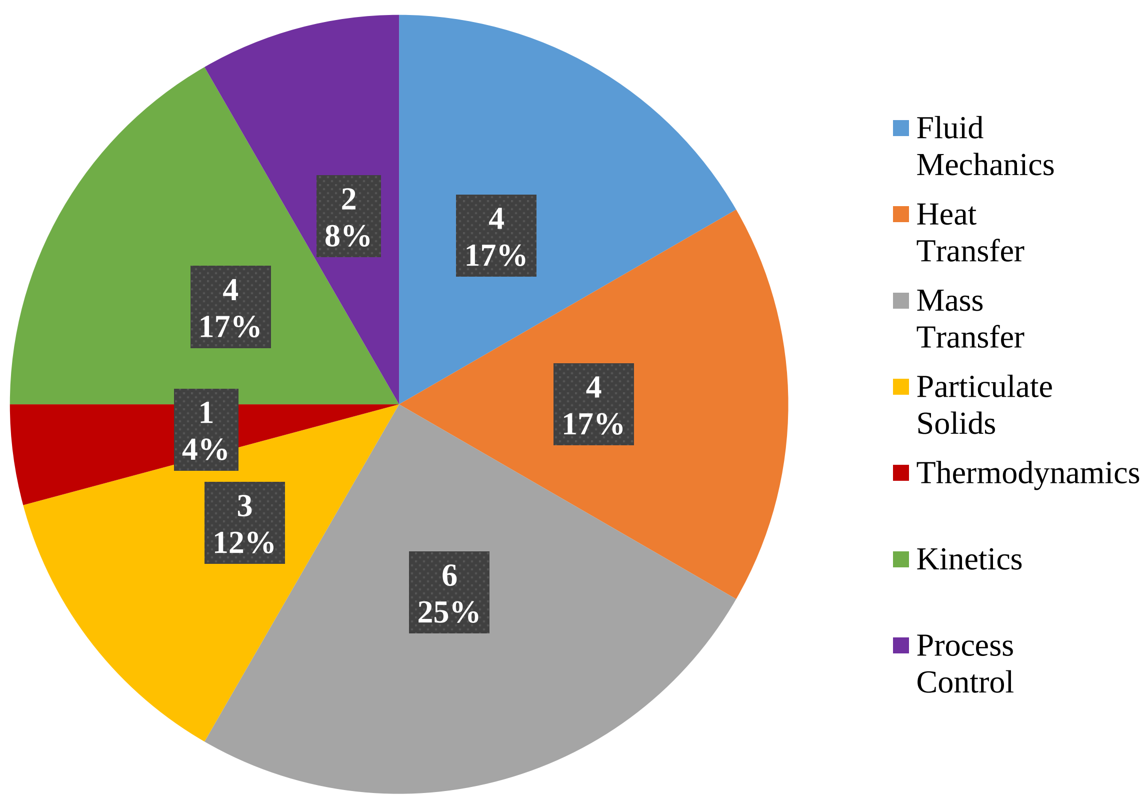

Figure 6.2.1: Total Number of Experimental Setups That Cover a Specific Subject Area

6.3 Breakdown of Experimental Setups with Respect to Origin

One of the objectives developed by Feisel and Rosa for instructional engineering laboratories is the element of "[d]esign" [4]. The authors describe design as "[d]esign, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials" [4]. The category of "Origin" has been developed to classify whether the element of design was present when developing individual Experimental Setups in the Chemical Engineering Laboratory. Two types of Origin have been identified for Experimental Setups in the Chemical Engineering Laboratory:

- **"In-House Development"** – Experimental Setups that are designed by professors and undergraduate/graduate students. These Experimental Setups afford students the opportunity to design and participate in the construction of the equipment that comprise the Experimental Setups.
- **"Purchased as Turnkey"** – Experimental Setups that are purchased as modular units with minor adjustments made by professors and/or students.

The classification of the individual Experimental Setups in the Chemical Engineering Laboratory according to the "Origin" category is presented in Table 6.5.2 and are visually depicted in Figure 6.3.1.

The Experimental Setups originating as in-house developments represent approximately three-quarters of the Experimental Setups. The significant bias towards in-house development is a reflection of the fact that all faculty in the Department of Chemical Engineering participate on a regular basis in the instruction of the undergraduate laboratory courses and have a strong interest in experimental development. As a result, the Chemical Engineering Laboratory provides opportunities for some students to obtain design experience.

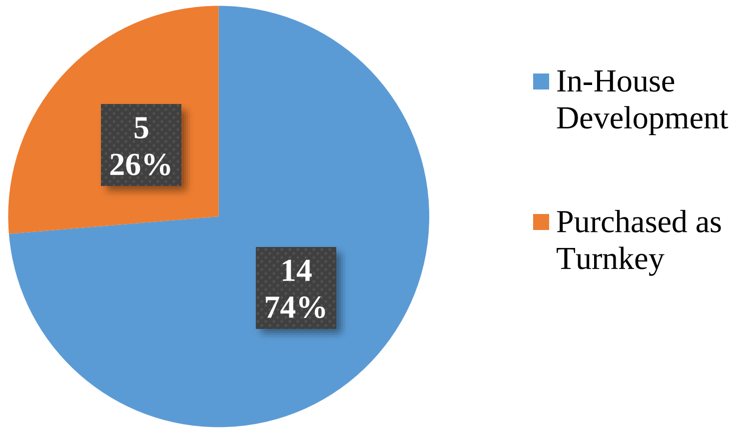

Figure 6.3.1: Origin of Experimental Setups

6.4 Breakdown of Experimental Setups with Respect to Operational Control

The development of practical skills for operating various types of instruments and equipment is a major objective of instructional engineering laboratories. In the seminal paper by Feisel and Rosa, these skills fall under "[o]bjective 8," "[p]sychomotor" [4]. Psychomotor skills range from simple manual tasks, such as opening a valve, to more complex tasks, such as operating a sophisticated piece of machinery. The category of "Operational Control" has been developed to classify the practical skills acquired by students while working on the Experimental Setups in the Chemical Engineering Laboratory. Three types of Operational Control have been identified based on the Standard Operating Procedures (SOP) for the Experimental Setups in the Chemical Engineering Laboratory:

- **"Manual"** – The Experimental Setup is operated entirely through manual manipulation and there is no automatic control associated with any of the process variables. This type of operational control develops engineering intuition, but is not representative of industrial practice.

- **“Manual and Automatic with DeltaV”** – The Experimental Setup is operated through a combination of manual manipulation and automatic control implemented with DeltaV. The automatic control can have multiple roles, such as maintaining critical process variables at desired set points, system startup, system shutdown, and safety interlocks. This type of operational control is representative of industrial practice, but important cause and effect relationships in the system may remain hidden from students behind the automatic functions. Initially, there is a steep learning curve associated with the DeltaV system, but once mastered, the DeltaV skills are transferrable across all Experimental Setups utilizing DeltaV.
- **“Manual and Automatic with Non-DeltaV”** – The Experimental Setup is operated through a combination of manual manipulation and automatic control implemented with a non-DeltaV control platform. This type of operational control is associated with turnkey Experimental Setups.

The classification of the individual Experimental Setups in the Chemical Engineering Laboratory according to the “Operational Control” category is presented in Table 6.5.2 and Figure 6.4.1.

Figure 6.4.1 shows that the operational control of the Experimental Setups almost equally divided between “Manual” (ten Experimental Setups) and “Manual and Automatic” (nine Experimental Setups). The “Manual and Automatic” group is dominated by DeltaV control (seven out of the nine Experimental Setups), which reflects a Chemical Engineering Department policy to standardize on the use of a single control platform. Overall, the mixture of “Operational Control” is well balanced and allows students to develop a wide range of psychomotor skills.

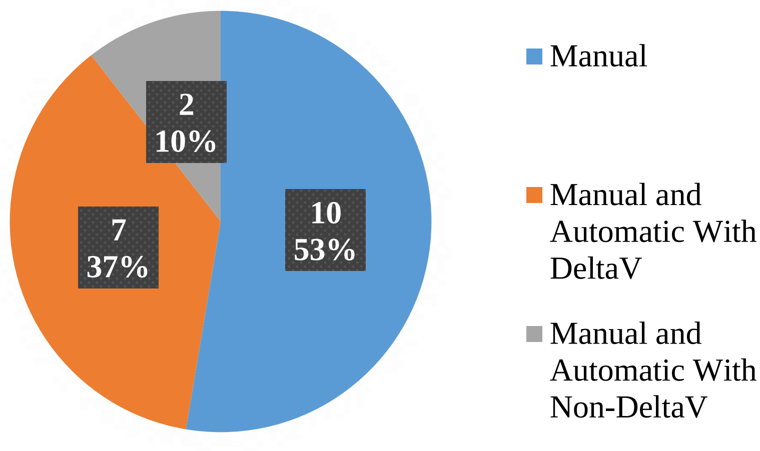

Figure 6.4.1: Operational Control of Experimental Setups

6.5 Breakdown of Experimental Setups with Respect to Degree of Automation

One of the objectives for instructional engineering laboratories set forth by Feisel and Rosa is the development of "[s]ensory [a]wareness" [4]. The authors describe "[s]ensory [a]wareness" as "[u]se the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems" [4]. The level of sensory awareness that can be developed by students when working on a particular Experimental Setup depends to a great extent on the level of automation of the Experimental Setup. In highly automated Experimental Setups, students have very little physical contact with the actual equipment and may not even be in close proximity to the actual equipment. The category of "Degree of Automation" has been developed to classify the level of sensory awareness acquired by students while working on the Experimental Setups in the Chemical Engineering Laboratory. Three "Degree of Automation" levels have been defined on a Likert-type scale based on the type of operational control, the presence (or not) of manually operated valves, and the presence (or not) of material handling and/or analysis:

- **“Low”** – The operational control of the Experimental Setup is “Manual” per the classification in Chapter 6.4.
- **“Medium”** – Automatic control is present on the Experimental Setup, but there is also manual manipulation associated with valves, material handling and/or material analysis.
- **“High”** – The Experimental Setup is operated mostly by automatic control and there is no material handling or analysis.

Based on the above classification, a high degree of automation corresponds to a low level of sensory awareness, whereas a low degree of automation corresponds to a high level of sensory awareness.

The classification of the individual Experimental Setups in the Chemical Engineering Laboratory according to the “Degree of Automation” category is presented in detail in Table 6.5.1 and in summary in Table 6.5.2.

In Table 6.5.1, the Experimental Setups are presented in order of “Degree of Automation,” from low to high. The Experimental Setups with a low degree of automation are only operated manually. The Experimental Setups with medium and high degrees of automation are all operated in “Manual and Automatic” mode. The differentiation is based on whether the experimental procedure includes material handling and/or analysis. Experimental Setups that involve material handling and/or analysis provide a higher degree of sensory awareness and are classified as having a medium degree of automation.

Figure 6.5.1 is based on the data from Table 6.5.2 and presents the breakdown of Experimental Setups in the Chemical Engineering Laboratory by the “Degree of Automation” category. A little more than half of all Experimental Setups (ten out of nineteen) provided a high level of sensory awareness because they are operated manually and have a low degree of automation. The other nine Experimental Setups are almost equally split between a high (five out of nine) and a medium (four out of nine) degree of automation. It should be noted that for all five Experimental Setups with a high degree of automation, it is not possible to execute the experiments without the automatic control due to safety and/or performance considerations. Overall, the mixture of Experimental Setups offers sufficient opportunities for students to develop their sensory awareness.

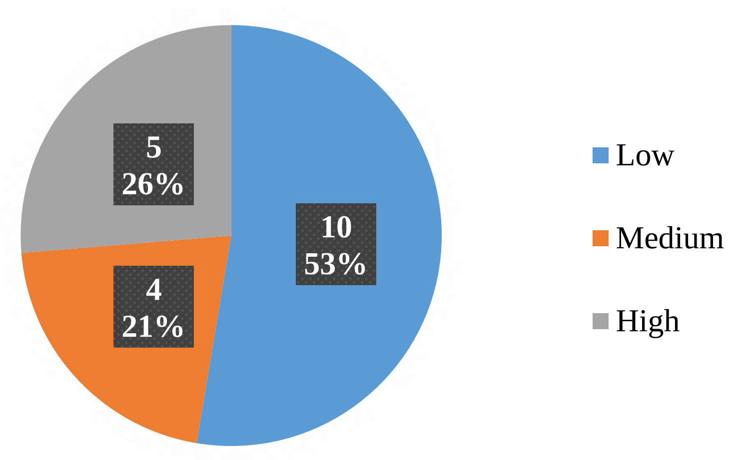

Figure 6.5.1: Degree of Automation of Experimental Setups

Table 6.5.1: Classification of Experimental Setups with Respect to Degree of Automation

Experimental Setup	Operational Control	Manually Operated Valves	Material Handling and/or Analysis	Degree of Automation
Agitated Tank	Manual	Yes	No	Low
Cooling Tower	Manual	Yes	No	Low
Drug Delivery	Manual	No	Yes	Low
Dryer	Manual	No	Yes	Low
Fluid Flow	Manual	Yes	No	Low
Fluidized Bed	Manual	Yes	No	Low
Othmer Still	Manual	Yes	Yes	Low
Reverse Osmosis	Manual	Yes	No	Low
Saponification Reaction	Manual	No	Yes	Low
Ultrafiltration	Manual	Yes	Yes	Low
Corning Column	Manual and Automatic with DeltaV	Yes	Yes	Medium
Filtration (Filter Press)	Manual and Automatic with DeltaV	Yes	Yes	Medium
Parr Reactor	Manual and Automatic with Non-DeltaV	Yes	Yes	Medium
Tubular Flow Reactor	Manual and Automatic with DeltaV	Yes	Yes	Medium
Fuel Cell	Manual and Automatic with Non-DeltaV	Yes	No	High
Instrumentation and Control	Manual and Automatic with DeltaV	Yes	No	High
Pumps	Manual and Automatic with DeltaV	Yes	No	High

Table 6.5.1 Continued

Experimental Setup	Operational Control	Manually Operated Valves	Material Handling and/or Analysis	Degree of Automation
Multipass Heat Exchanger	Manual and Automatic with DeltaV	Yes	No	High
Tangential Flow Filtration	Manual and Automatic with DeltaV	Yes	No	High

Table 6.5.2: Classification of Individual Experimental Setups

Experimental Setup	Data Acquisition	Subject Area	Origin	Operational Control	Degree of Automation
Drug Delivery	Local Displays without Historization	Mass Transfer	In-House Development	Manual	Low
Dryer	Local Displays without Historization	Heat Transfer Mass Transfer	Purchased as Turnkey	Manual	Low
Fluid Flow	Local Displays without Historization	Fluid Mechanics	In-House Development	Manual	Low
Othmer Still	Local Displays without Historization	Thermo-dynamics	In-House Development	Manual	Low
Parr Reactor	Local Displays without Historization	Kinetics	Purchased as Turnkey	Manual and Automatic with Non-DeltaV	Medium
Cooling Tower	Local Displays with Local Historization	Heat Transfer Mass Transfer	Purchased as Turnkey	Manual	Low
Fuel Cell	Local Displays with Local Historization	Kinetics Mass Transfer	Purchased as Turnkey	Manual and Automatic with Non-DeltaV	High
Saponification Reaction	Local Displays with Local Historization	Kinetics	In-House Development	Manual	Low
Ultrafiltration	Local Displays with Local Historization	Particulate Solids	Purchased as Turnkey	Manual	Low

Table 6.5.2 Continued

Experimental Setup	Data Acquisition	Subject Area	Origin	Operational Control	Degree of Automation
Fluidized Bed	DeltaV GUI with DeltaV Historian	Fluid Mechanics	In-House Development	Manual	Low
Agitated Tank	Local Displays with DeltaV Historian	Heat Transfer	In-House Development	Manual	Low
Corning Column	Local Displays with DeltaV Historian	Mass Transfer	In-House Development	Manual and Automatic with DeltaV	Medium
Filtration (Filter Press)	Local Displays with DeltaV Historian	Particulate Solids	In-House Development	Manual and Automatic with DeltaV	Medium
Instrumentation and Control	Local Displays with DeltaV Historian	Fluid Mechanics Process Control	In-House Development	Manual and Automatic with DeltaV	High
Multipass Heat Exchanger	Local Displays with DeltaV Historian	Heat Transfer	In-House Development	Manual and Automatic with DeltaV	High
Pumps	Local Displays with DeltaV Historian	Fluid Mechanics	In-House Development	Manual and Automatic with DeltaV	High
Reverse Osmosis	Local Displays with DeltaV Historian	Mass Transfer	In-House Development	Manual	Low
Tangential Flow Filtration	Local Displays with DeltaV Historian	Particulate Solids	In-House Development	Manual and Automatic with DeltaV	High

Table 6.5.2 Continued

Experimental Setup	Data Acquisition	Subject Area	Origin	Operational Control	Degree of Automation
Tubular Flow Reactor	Local Displays with DeltaV Historian	Kinetics	In-House Development	Manual and Automatic with DeltaV	Medium
		Process Control			

7. ANALYSIS OF LABORATORY PROJECT ASSIGNMENTS IN THE UNDERGRADUATE LABORATORY COURSES

7.1 Description of the CHE 411/412/413 Laboratory Sequence at Rose-Hulman

As noted earlier, the Chemical Engineering Laboratory sequence offers students the opportunity to gain practical and hands-on experience with processes that are commonplace throughout industry. As such, the Chemical Engineering Laboratory sequence is arguably the most important and practical set of classes that a Chemical Engineering student will take. At Rose-Hulman, the Chemical Engineering Laboratory sequence consists of three courses taken during three consecutive quarters, Spring Quarter, Fall Quarter, and Winter Quarter. Rose-Hulman's Chemical Engineering Department offers the following description of the three courses that comprise the Chemical Engineering Laboratory sequence:

"**CHE 411 Chemical Engineering Laboratory I:**

Principles underlying momentum, mass and energy transfer and the applications of equipment used to accomplish such transfer, introduction to laboratory concepts in data collection, record keeping, interpretation and analysis, and instrumentation including experimental error analysis, regression, model formulation, experimental design, and instrumentation. Written and oral reports are required. Formal instruction on written and oral communication and teaming will be provided.

CHE 412 Chemical Engineering Laboratory II:

Continuation of principles underlying momentum, mass and energy transfer with some emphasis on kinetics, applications of equipment used to accomplish such transfer.

CHE 413 Chemical Engineering Laboratory III:

Continuation of CHE 412 with emphasis on process control and kinetics" [25].

During the course of the Chemical Engineering Laboratory sequence, students are involved with a total of five projects, one project during CHE 411, and two projects during both CHE 412 and CHE 413. These projects cover chemical engineering topics such as fluid transport, heat transfer, mass transfer, heat and mass transfer, kinetics, particulate solids, mechanical separations, instrumentation and control, and thermodynamics. At the conclusion of each project, each student is required to write a formal report detailing their group's findings as well as the theory applied, equipment, and procedures used. Additionally, at the conclusion of each quarter, each group is required to give a presentation of their first project of the quarter to both their peers and faculty from the Chemical Engineering Department. As part of these presentations, both the students' peers and the faculty are afforded the opportunity to ask the students questions, thereby ensuring that students clearly understand the concepts they are expected to learn from their project as well as the Chemical Engineering Laboratory sequence as a whole.

7.2 Analysis of CHE 411/412/413 Assignments Between AY 2013-14 and AY 2016-17

Recent data between AY 2013-14 and AY 2016-17 were available through the Chemical Engineering Laboratory Coordinator on the project assignments for CHE 411/412/413.

The data were first analyzed to determine the utilization of each Chemical Engineering Laboratory project by finding the number of times each project was utilized per quarter knowing that the maximum possible uses per year is eleven. The maximum possible uses was determined to be eleven since an Experimental Setup can be utilized a maximum of three times during Spring Quarter, three times per week and once during each Laboratory session, and four times each during Fall Quarter and Winter Quarter, two times per week and twice during each Laboratory session. The calculation of the maximum use is shown below in Equation 5 where S stands for Spring Quarter, F stands for Fall Quarter, and W stands for Winter Quarter.

$$Max\ Use =$$

$$3 \cdot (S\ 2012 - 13) + 4 \cdot (F\ 2013 - 14) + 4 \cdot (W\ 2013 - 14) \tag{5}$$

$$+ \cdots + 3 \cdot (S\ 2015 - 16) + 4 \cdot (F\ 2016 - 17) + 4 \cdot (W\ 2016 - 17)$$

The number of times each project was utilized per year was determined as follows below in Equation 6.

$$Actual\ Use =$$

$$(S\ 2012 - 13) + (F\ 2013 - 14) + (W\ 2013 - 14) \tag{6}$$

$$+ \cdots + (S\ 2015 - 16) + (F\ 2016 - 17) + (W\ 2016 - 17)$$

This number was then divided by the maximum possible uses per year to determine the utilization of each Chemical Engineering Laboratory project, as is shown in Equation 7 below.

$$Utilization = \frac{Actual\ Use}{Max\ Use} \cdot 100\% \tag{7}$$

The reader should note that not all of the Experimental Setups have been available for the entire timespan between AY 2013-14 and AY 2016-17; therefore, the maximum possible uses was adjusted to account for the timespan that each Experimental Setup was available in the Chemical Engineering Laboratory between AY 2013-14 and AY 2016-17.

The data were also analyzed to determine the ratio of pilot scale projects to bench scale projects that a student does over the course of the Chemical Engineering Laboratory sequence. There were six possible categories into which a student could fall ranging from 0:5, where a student experienced zero pilot scale projects and five bench scale projects over the course of the Chemical Engineering Laboratory sequence, to 5:0, where a student experienced five pilot scale projects and zero bench scale projects over the course of the Chemical Engineering Laboratory sequence. The number of students in each ratio category was then divided by the total number of students to determine the average pilot scale to bench scale ratio.

7.2.1 Utilization of Experimental Setups

The utilization of the Experimental Setups in the Chemical Engineering Laboratory is presented in Table B.1 in Appendix B and in Figure 7.2.1.1. It should be noted that utilization of Experimental Setups is a function of operability/physical condition and faculty preferences. Figure 7.2.1.1 shows that six Experimental Setups have a utilization that is greater than eighty percent (80%); furthermore, of those six Experimental Setups, four Experimental Setups have a utilization that is greater than ninety percent (90%). Additionally, seven Experimental Setups have a utilization between forty percent (40%) and sixty percent (60%). The utilization of the Experimental Setups is a function of operability, i.e., the physical condition of the Experimental Setups, and faculty preferences; therefore, these data can be used to determine which

Experimental Setups are historically underutilized due to both issues with operations and disinterest by faculty members from lack of experience or lack of industrial/theoretical application.

Earlier in Chapter 5.3.1 the reader was asked to take special notice of the second most expensive Experimental Setup in terms of purchase cost, the Tangential Flow Filtration Experimental Setup. Figure 7.2.1.1 shows that the Tangential Flow Filtration Experimental Setup has a utilization of zero percent (0%), which does not correspond well with the Experimental Setup having the second most expensive original purchase cost. The reason for the zero percent (0%) utilization of the Tangential Flow Filtration Experimental Setup is due to the fact that the Experimental Setup has remained inoperable since its original installation in the Chemical Engineering Laboratory. The reasons the Tangential Flow Filtration Experimental Setup has remained inoperable are because a suitable, yet affordable medium that would require filtering has yet to be found and the instrumentation and data acquisition have not yet been configured. Currently, multiple faculty members in the Chemical Engineering Department and Chemical Engineering students are collaborating to bring the Tangential Flow Filtration Experimental Setup into an operable condition.

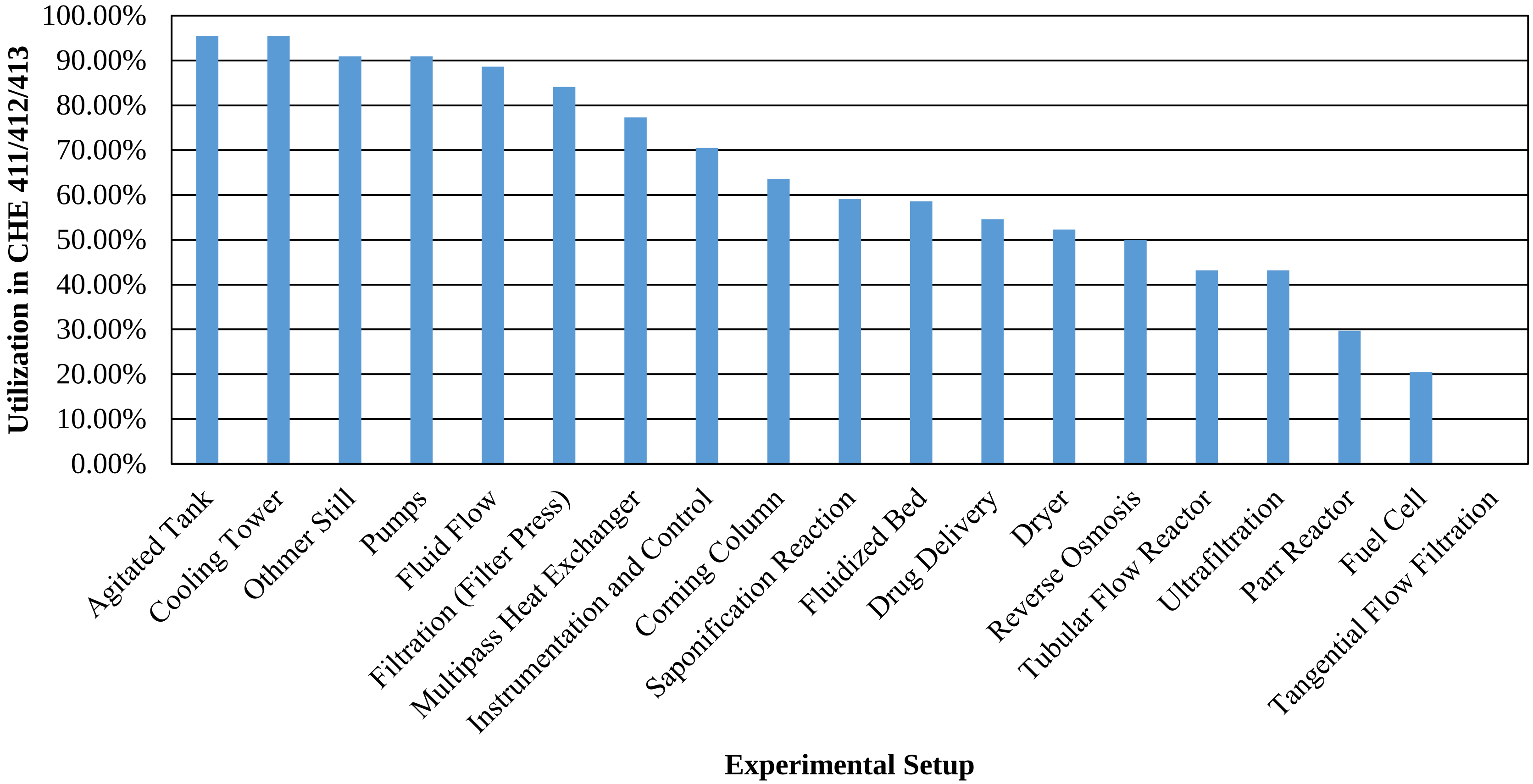

Figure 7.2.1.1: Utilization of Experimental Setups in CHE 411/412/413 Between AY 2013-14 and AY 2016-17

7.2.2 Breakdown of Pilot Scale to Bench Scale Ratio

Figure 7.2.2.1 on the following page details the breakdown of the calculated pilot scale to bench scale ratio for the project assignments for CHE 411/412/413 between AY 2013-14 and AY 2016-17. Figure 7.2.2.1 shows that a pilot scale to bench scale ratio of zero pilot scale Experimental Setups to five bench scale Experimental Setups (0:5) never occurred in the data analyzed. Furthermore, a pilot scale to bench scale ratio of one pilot scale Experimental Setup to four bench scale Experimental Setups (1:4) occurred a very low percentage of the time; therefore, there are a low number of Chemical Engineering students (2%) who do not receive significant exposure to industrial pilot scale Experimental Setups. Pilot scale to bench scale ratios of three pilot scale Experimental Setups to two bench scale Experimental Setups (3:2), four pilot scale Experimental Setups to one bench scale Experimental Setup (4:1), and five pilot scale Experimental Setups to zero bench scale Experimental Setups (5:0) occurred approximately eighty-five percent (85%) of the time, which is consistent with the higher number of pilot scale Experimental Setups available in the Chemical Engineering Laboratory.

As noted earlier in Chapter 5.5, Hesketh and Slater outline the merits of having both pilot scale and bench scale Experimental Setups [20]. Pilot scale Experimental Setups give students a more realistic depiction of actual processing equipment; however, bench scale Experimental Setups are generally less expensive, less complex, require less time for experimentation, occupy less space, and can be easily relocated [20]. Consequently, the ideal pilot scale to bench scale ratios are two pilot scale Experimental Setups to three bench scale Experimental Setups (2:3) and three pilot scale Experimental Setups to two bench scale Experimental Setups (3:2), which occurred approximately fifty percent (50%) of the time; therefore, a high percentage of Chemical Engineering students are receiving a good mixture of pilot scale and bench scale Experimental

Setups that will provide them a well-rounded Chemical Engineering education as well as the opportunity to obtain relevant industry experience.

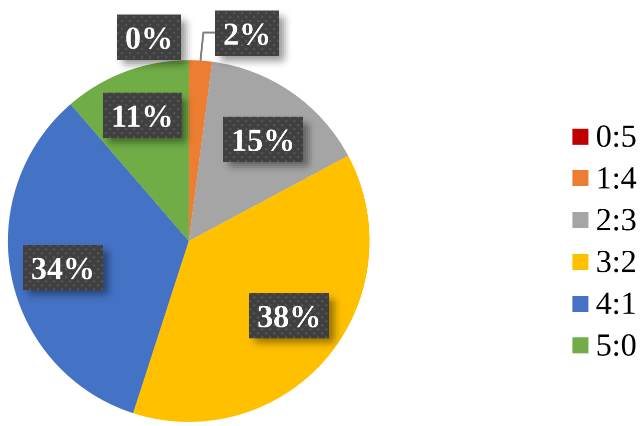

Figure 7.2.2.1: Pilot Scale to Bench Scale Ratio in CHE 411/412/413 Between AY 2013-14 and AY 2016-17

8. FACULTY INTERESTS IN NEW ASSETS

Faculty members within the Chemical Engineering Department were interviewed to determine what projects as well as equipment they would have an interest in seeing in the Chemical Engineering Laboratory space within the next fifteen years. The equipment that a Chemical Engineering Department faculty member expressed interest in could be for the purpose of instruction, research, and/or special projects.

8.1 Catalytic Reactor Unit [26]

A faculty member expressed interest in a catalytic reactor unit since the Chemical Engineering Department currently lacks a catalytic unit. Catalysts are utilized throughout industry in order to increase the rate of chemical reactions; therefore, having a catalytic unit would offer students hands on experience with respect to something they will likely see and use throughout their careers. A catalytic reactor unit would cover the chemical engineering subject areas of heat and mass transfer, kinetics, and fluid transport. The catalytic unit could be either bench scale or pilot scale. In an ideal situation, the catalytic unit would be utilized for a liquid-gas phase reaction.

8.2 Crystallization Reaction [26]

A faculty member expressed interest in a unit capable of performing a crystallization reaction. A crystallization reaction has been suggested by alumni in the past due to the significant use of crystallization reactions in the food processing industry. A crystallization reaction unit would give students exposure to a different industry that many may have an interest in, thereby giving said students an advantage during interviews. Additionally, crystallization reactions are not covered heavily in Rose-Hulman's Chemical Engineering curriculum; therefore, giving students exposure to a unit capable of performing a crystallization reaction would increase their chances of success in a field that utilizes crystallization reactions.

8.3 Polarized Microscope [27]

A faculty member expressed interest in a polarized microscope for the purpose of research and instruction related to materials science and materials characterization. The polarized microscope would be a bench scale unit with a footprint of approximately 3 ft^2.

8.4 Bench Scale Reverse Osmosis System [27]

A faculty member expressed interest in a bench scale reverse osmosis system. This bench scale system would be for the purpose of undergraduate research as well as the Chemical Engineering Laboratory sequence; however, it would differ from the current reverse osmosis system in the Chemical Engineering Laboratory. A bench scale reverse osmosis system would cover the chemical engineering subject areas of fluid transport and mass transfer. The bench scale reverse osmosis system would have a footprint of approximately 15 ft^2.

8.5 Membrane Distillation System [27; 28]

Faculty members expressed interest in a membrane distillation system for the purpose of the Chemical Engineering Laboratory sequence. This system would be a bench scale system and is of particular interest because membrane distillation is currently an emerging technology.

Additionally, membrane distillation is currently relevant to the food industry. A membrane distillation system would cover the chemical engineering subject areas of heat and mass transfer, fluid transport, and thermodynamics; however, membrane distillation is a unique and different way to explore said subject areas of chemical engineering.

8.6 High Temperature Furnace [27]

A faculty member expressed interest in a high temperature furnace for the purpose of an elective course related to materials processing. A high temperature furnace is integral to materials processing since elevated temperatures are required in order to process raw materials into more useable materials. A high temperature furnace would cover the chemical engineering subject areas of heat and mass transfer, thermodynamics, and materials science, and would be a necessary piece of equipment for both electives and student clubs. The high temperature furnace would have a footprint of approximately 6 ft^2. Unfortunately, there is a safety concern with a high temperature furnace due to the high temperature generated in the unit.

8.7 Future Experimental Setup – Fermenter [29]

The Chemical Engineering Department is currently in the process of installing a fermenter in the Special Projects Laboratory (O-226) in order to replace a non-functional fermenter that was previously utilized. Once installed, this new fermenter will be for the purpose of an experimental fermentation process that covers the chemical engineering subject areas of mass transfer and kinetics of biological systems. This Experimental Setup will be utilized for the Chemical Engineering Laboratory sequence as well as undergraduate and graduate research. The fermenter will have a footprint of approximately 24 ft^2. A possible future addition to the newly installed fermenter is a biosafety laboratory hood.

8.8 Expansion of Reverse Osmosis System – Installation of Tank [28; 30]

Faculty members expressed interest in a modification/expansion being made to the reverse osmosis system that resides in the Chemical Engineering Laboratory. The modification/expansion would require the installation of a tank to the current reverse osmosis system. By installing said tank, a closed loop could be established, whereby differing concentrations of feed could be introduced. Making this modification/expansion would increase the utility and learnability from the current reverse osmosis system.

8.9 Chromatography System [31]

A faculty member expressed interest in a chromatography system. The chromatography system would be a portable, bench scale unit. The bench scale chromatography system would have a footprint of approximately 25 ft^2. This unit could be purchased as a turnkey for approximately $30,000.00. This system would be for the purpose of the Chemical Engineering Laboratory sequence, EM103, CHE546, undergraduate research, and graduate research. A chromatography system would cover the chemical engineering subject areas of mass transfer, kinetics, particulate solids, mechanical separations, thermodynamics, bioseparations, and materials. Operational control of the chromatography system would be manual and non-DeltaV. Additionally, data acquisition would be accomplished through local displays and local historization. Due to the nature of a chromatography system, sample collection and sample analysis would be necessary. Approximately 50% of the control would be accomplished through hands on manipulation while 50% of the control would be automatic. A chromatography system would allow for students to develop their skills for the pharma field; furthermore, some programming skills would be necessary in order to operate the system.

8.10 Liquid Level in a Tank [32]

A faculty member expressed interest in a basic process control Experimental Setup for the purpose of the Chemical Engineering Laboratory sequence. This system would ideally allow for the liquid level in a tank to be both monitored and controlled. A basic process control system such as this would allow for direct feedback to students; therefore, students would be able to directly focus on the chemical engineering subject area of process control, and directly see the effect of tuning parameters on an Experimental Setup. A basic process control Experimental Setup would give students exposure to the process control relationships that are integral to succeeding in a process control field.

8.11 Adsorption Project [32]

A faculty member expressed interest in an Experimental Setup related to the topic of adsorption for the purpose of the Chemical Engineering Laboratory sequence. An adsorption system would cover the chemical engineering subject areas of adsorption kinetics and fluid mechanics. Adsorption is commonplace throughout industry and industrial applications include catalysis, pharmaceuticals, and water treatment. An adsorption bed is a possible Experimental Setup related to the topic of adsorption where liquid phase to solid phase adsorption could be studied.

8.12 Analytical Instruments for Materials Characterization [32]

A faculty member expressed interest in Analytical Instruments related to materials characterization for the purpose of undergraduate and graduate research. Possible Analytical instruments that could be utilized for materials characterization include a dynamic mechanical analysis (DMA), differential scanning calorimeter (DSC), microscopes, etc. Analytical Instruments related to materials characterization would cover the chemical engineering subject area of materials science.

8.13 Future Experimental Setup – Fluid Flow with Fieldbus Instruments [33]

The Chemical Engineering Department is currently in the process of installing a new Fluid Flow Experimental Setup in the High Bay Laboratory (O-100) in order to replace an antiquated Fluid Flow Experimental Setup that was previously utilized. Once installed, this new Experimental Setup will cover the chemical engineering subject areas of fluid mechanics and instrumentation and control. This Experimental Setup will be utilized for the Chemical Engineering Laboratory sequence and will provide students with exposure to modern instrumentation that utilizes Fieldbus and wireless communication. The new Fluid Flow Experimental Setup will have a footprint that occupies both the footprint of the current Fluid Flow Experimental Setup and the adjacent space that is currently used for storage.

8.14 Improvement of Parr Reactor [30]

A faculty member expressed interest in improvements being made to the existing Parr Reactor Experimental Setup in terms of instrumentation. Improving the instrumentation on the Parr Reactor Experimental Setup would allow for better control, data acquisition, and reliability of the Experimental Setup, which would thereby increase the utility and learnability from the current Parr reactor system.

8.15 Flexible Control and Data Acquisition Options for Experimental Setups [30]

A faculty member expressed interest in ancillary/supplemental options for control and data acquisition that have a greater degree of flexibility being explored for Experimental Setups. These ancillary/supplemental options for control and data acquisition would be in addition to the current DeltaV system. The exploration and implementation of such options would allow for better control, data acquisition, and reliability of the Experimental Setups since Experimental Setups could still be fully utilized if the DeltaV system became inoperable, which would thereby increase the utility and learnability of the Experimental Setups.

8.16 Pneumatic Conveying [34]

A faculty member expressed interest in a pneumatic conveying Experimental Setup for the purpose of the Chemical Engineering Laboratory sequence. A pneumatic conveying system would cover the chemical engineering subject area of particle technology, and will provide students with exposure to both dense phase and dilute phase, pressure drops, hopper flows, and cyclone separators. Additionally, a pneumatic conveying system offers the possibility for troubleshooting, a skill that is integral to a student’s success as a chemical engineer. Pneumatic conveying systems are used throughout the food and ingredients industry. This Experimental Setup could be implemented along the walls of one of the laboratories in the Chemical Engineering Laboratory.

8.17 Improvement of Fuel Cell [35]

A faculty member expressed interest in improvements being made to the existing Fuel Cell Experimental Setup. The following issues with the current system include the actual fuel cell utilized by the system needing to be replaced and the physical fuel cell system experiencing communication issues with the control and data acquisition system. Additionally, the company through which the turnkey setup was purchased is no longer in business; therefore, any changes or modifications will likely need to be performed in-house. Revamping the Fuel Cell Experimental Setup to eliminate the issues listed above would allow for better control, data acquisition, and reliability of the Experimental Setup, which would thereby increase the utility and learnability from the current fuel cell system. Furthermore, fuel cells are currently being investigated as a power generation technology in various industries including automobiles and electricity production; therefore, fuel cells are an emerging technology that can give students an edge in their professional careers.

8.18 Improvement of Othmer Still [35]

A faculty member expressed interest in improvements being made to the existing Othmer Still Experimental Setup. The current system is open to the atmosphere and any changes in ambient pressure due to weather cannot be accounted for; therefore, pressure fluctuations are common with the current system, which in some cases results in thermodynamically inconsistent data. Additionally, Othmer stills must be specially made to allow for the collection of both liquid and vapor samples; therefore, a professional glassblower will need to be employed in order to replace the current Othmer Still Experimental Setup. Revamping the Othmer Still Experimental Setup to eliminate the pressure issue listed above would allow for the pressure to be maintained at a constant pressure, which would thereby increase the reliability of the Experimental Setup as well as the utility and learnability from the current system.

8.19 Thermodynamic Cycle [35]

A faculty member expressed interest in an Experimental Setup related to a thermodynamic cycle for the purpose of the Chemical Engineering Laboratory sequence. A thermodynamic cycle system would cover the chemical engineering subject area of thermodynamics. Additionally, a thermodynamic cycle Experimental Setup offers the possibility for comparison to Aspen, which would allow for students to compare experimental data to simulated data. In the past, a turnkey Experimental Setup for a Rankine power cycle was available in the Chemical Engineering Laboratory; however, the equipment was unreliable and the Experimental Setup became unusable. If an Experimental Setup related to a thermodynamic cycle is instituted in the Chemical Engineering Laboratory, it will likely be an in-house development. Possible Experimental Setups related to thermodynamic cycles include a power generation cycle or a refrigeration cycle.

8.20 Alternative Energy [35]

A faculty member expressed interest in an Experimental Setup related to the topic of alternative energy, such as wind energy or solar energy, for the purpose of the Chemical Engineering Laboratory sequence. An Experimental Setup related to the topic of alternative energy would cover the chemical engineering subject areas of thermodynamics and green energy. Possible Experimental Setups that could be utilized to explore alternative energy include a solar cell or a wind mill. One concern with solar cells and wind mills is that they are typically operated outdoors; therefore, a simulated environment of sun or wind would be required for the successful implementation of an Experimental Setup related to the topic of alternative energy.

8.21 Separations Project [36]

A faculty member expressed interest in an Experimental Setup related to the topic of separations for the purpose of the Chemical Engineering Laboratory sequence. An Experimental Setup pertaining to separations would cover the chemical engineering subject area of separations and possibly other subject areas depending on what separation method is selected. Possible Experimental Setups related to the topic of separations include a chromatography column and a liquid-liquid extraction system, both of which are common throughout the pharmaceutical industry. An additional Experimental Setup related to the topic of separations would increase the number of students that are exposed to the subject area of separations during the Chemical Engineering Laboratory sequence.

8.22 Packed Bed Reactor [36]

A faculty member expressed interest in a packed bed reactor Experimental Setup for the purpose of the Chemical Engineering Laboratory sequence. A packed bed reactor would cover the chemical engineering subject area of kinetics. An additional Experimental Setup related to the topic of kinetics would increase the number of students that are exposed to the subject area of kinetics during the Chemical Engineering Laboratory sequence; however, kinetics is currently covered by four Experimental Setups, which makes it one of the most covered subject areas. One possible packed bed reactor Experimental Setup includes an immobilized enzyme packed bed reactor.

9. COMPARISON TO OTHER INSTITUTIONS

The assets in the Chemical Engineering Laboratory at Rose-Hulman were compared to the assets available in the Chemical Engineering Laboratories of other institutions with similarities to Rose-Hulman. Table 9.1 below details the institutions selected for comparison as well as the reason each institution was selected for comparison based on their similarity to Rose-Hulman, e.g., a small undergraduate enrollment, a high ranking according to U.S. News & World Report's Undergraduate Engineering Program rankings, etc.

Table 9.1: Comparator Institutions and Reason(s) for Selection

Comparator Institution	Reason(s) for Selection of Comparator Institution
Bucknell University	• Small Undergraduate Enrollment (3,500) [37] • Highly Ranked (Seventh – Doctorate Not Offered) [38]
Cooper Union	• Small Undergraduate Enrollment (900) [39] • Highly Ranked (Ninth – Doctorate Not Offered) [38]
Michigan Technological University	• Small Undergraduate Enrollment (5,750) [40] • Well Documented and Described Laboratory Facilities [41; 42]
Purdue University	• Geographic Proximity (Indiana) [43] • Highly Ranked (Ninth – Doctorate Offered) [44]
Rowan University	• Relatively Small Undergraduate Enrollment (13,250) [45]

The reader is advised to consult Appendices D, E, F, G, and H for an explanation of what merited the inclusion of a specific institution in the comparative survey as well as the Experimental Setups a specific institution has in its Chemical Engineering Laboratory for Bucknell University, Cooper Union, Michigan Technological University, Purdue University, and Rowan University, respectively.

9.1 Limitations of the Comparative Survey

The purpose of the comparative survey was to compare the assets in the Chemical Engineering Laboratory at Rose-Hulman to the assets available in the Chemical Engineering Laboratories of other highly regarded/ranked colleges/universities. Unfortunately, the only information that was found for other institutions was what was available on each institution's website, which is likely not an accurate reflection of the assets other colleges/universities have available for use in their respective Chemical Engineering Laboratories. Rose-Hulman does not currently have an accurate or up-to-date portrayal of the assets available in its own Chemical Engineering Laboratory on its own website; therefore, the information available on other colleges'/universities' websites should be considered inconclusive at best.

9.2 Experimental Setups at Rose-Hulman Institute of Technology with a Corresponding Equivalent at Surveyed Institutions

Table 9.2.1 displays the Experimental Setups at Rose-Hulman that other surveyed institutions have as well. The two Experimental Setups that were seen at the greatest proportion of institutions include the Corning Column (Distillation Column) Experimental Setup and the Multipass Heat Exchanger Experimental Setup. These Experimental Setups cover distillation and heat exchange, which are two industrial processes that are commonplace throughout industry. The remainder of Experimental Setups listed in Table 9.2.1 are similarly frequently seen in industry and will likely be encountered by students during their careers.

Table 9.2.1: Experimental Setups at R.H.I.T. with a Corresponding Equivalent at Surveyed Institutions

Rose-Hulman Institute of Technology Experimental Setup	Surveyed Schools with Similar Experimental Setup
Corning Column (Distillation Column)	Bucknell University Cooper Union Michigan Technological University Purdue University Rowan University
Multipass Heat Exchanger	Bucknell University Cooper Union Michigan Technological University Rowan University
Reverse Osmosis	Bucknell University Cooper Union Michigan Technological University Rowan University
Ultrafiltration	Bucknell University Michigan Technological University Rowan University
Cooling Tower	Michigan Technological University Purdue University
Dryer	Cooper Union Purdue University
Filtration (Filter Press)	Cooper Union Michigan Technological University
Fluidized Bed	Michigan Technological University Rowan University
Tangential Flow Filtration	Bucknell University Michigan Technological University
Tubular Reactor	Cooper Union Rowan University
Fluid Flow	Cooper Union
Instrumentation and Control	Michigan Technological University
Parr Reactor	Cooper Union
Pumps	Michigan Technological University
Saponification Reaction	Rowan University

9.3 Experimental Setups at Rose-Hulman Institute of Technology without a Corresponding Equivalent at Surveyed Institutions

The following Experimental Setups at Rose-Hulman Institute of Technology do not have a corresponding equivalent at any of the surveyed institutions:

- Agitated Tank
- Drug Delivery
- Fuel Cell
- Othmer Still

The four Experimental Setups listed above were not found to be in place in the Chemical Engineering Laboratory at any of the surveyed institutions. As noted previously, this may be due to the fact that the information obtained is not entirely accurate; however, it may also be due to the fact that drug delivery, fuel cells, and Othmer stills are not as frequently seen in industry as those Experimental Setups listed in Table 9.2.1.

9.4 Experimental Setups at Surveyed Institutions without a Corresponding Equivalent at Rose-Hulman Institute of Technology

Table 9.4.1 displays the Experimental Setups at surveyed institutions that Rose-Hulman does not have. The Experimental Setup that was seen at the largest proportion of institutions, but not at Rose-Hulman, was an Experimental Setup for the purpose of liquid-liquid extraction. A liquid-liquid extraction Experimental Setup covers the chemical engineering subject area of separations, which is commonplace throughout industry. It should be noted that Chapter 8.21 details a faculty interest in the addition of a separations Experimental Setup in the Chemical

Engineering Laboratory at Rose-Hulman with liquid-liquid extraction being one of the possible options suggested.

Similarly, the Experimental Setup that was seen at the second largest proportion of institutions, but not at Rose-Hulman, was an Experimental Setup for the purpose of gas-liquid absorption.

Table 9.4.1: Experimental Setups at Surveyed Institutions without a Corresponding Equivalent at R.H.I.T.

Experimental Setup without a Corresponding Equivalent at Rose-Hulman Institute of Technology	Surveyed Schools with Experimental Setup
Liquid-Liquid Extraction	Cooper Union Michigan Technological University Purdue University Rowan University
Gas-Liquid Absorption	Bucknell University Purdue University Rowan University
Ion Exchange Unit	Bucknell University Purdue University
Membrane Air Separation	Cooper Union Purdue University
Polymerization Reactor	Michigan Technological University Purdue University
Bench Scale Packed Bed Catalytic Reactor	Purdue University
Catalytic Reactor System with FTIR	Rowan University
Fixed Bed Reactor	Michigan Technological University
Capillary Viscometer	Michigan Technological University
Crystallization Process	Purdue University
Electrodialysis Membrane System	Rowan University
Pervaporation Membrane System	Rowan University
Fermentation	Rowan University
Immobilized Enzyme Reactor	Purdue University
Soluble Enzymatic Reactor	Purdue University
Climbing Film Evaporator	Rowan University

Table 9.4.1 Continued

Experimental Setup without a Corresponding Equivalent at Rose-Hulman Institute of Technology	Surveyed Schools with Experimental Setup
Flash Vaporizer	Purdue University
Flooding Point of a Packed Column	Cooper Union
Multiphase Mixing	Rowan University
Spray Dryer	Bucknell University
Vacuum Drying	Michigan Technological University
Specialty Chemical Pilot Plant	Rowan University

It should be noted that the Experimental Setups of liquid-liquid extraction, gas-liquid absorption, and membrane air separation listed in Table 9.4.1 existed at Rose-Hulman at one time or another; however, the Experimental Setups were decommissioned after lying dormant for a significant period of time. Additionally, the ion exchange unit Experimental Setup is a topic that is currently covered in the curriculum of the laboratory portion of Physical Chemistry at Rose-Hulman; therefore, Chemical Engineering students do receive hands-on, laboratory exposure to an ion exchange Experimental Setup.

Faculty interest in the addition of Experimental Setups has been documented for the following Experimental Setups at surveyed institutions that do not have a corresponding equivalent at Rose-Hulman:

- Liquid-Liquid Extraction
- Bench Scale Packed Bed Catalytic Reactor
- Catalytic Reactor System with FTIR
- Crystallization Process
- Fermentation – Future Experimental Setup
- Immobilized Enzyme Reactor

The six Experimental Setups listed above are available at one or more of the surveyed institutions, but do not currently exist at Rose-Hulman; however, faculty within the Chemical Engineering Department have expressed interest in the addition of similar Experimental Setups to the Chemical Engineering Laboratory at Rose-Hulman as detailed in Chapter 8.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The purpose of this work was to fulfill the immediate need for information for the ongoing Departmental discussion on the future role of the Chemical Engineering Laboratory in the undergraduate courses. To meet those needs, the following was accomplished:

Up-to-date floor plans of all ten laboratory facilities were created to document the current allocation of floor and countertop spaces. In a majority of the laboratories, the free floor space, including egress and regress space, is less than forty-five percent (45%), which does not provide an ample amount of space for future additions of pilot scale Experimental Setups based on the floor plans and analysis provided in Chapter 4. In contrast, the free countertop space in most of the laboratories is greater than eighty percent (80%), which can support future additions in benchtop Experimental Setups and Analytical Instruments.

A total of sixty-seven individual assets in the Chemical Engineering Laboratory have been catalogued. The purchase cost of all cataloged assets was $1,017,427.00. Of the sixty-seven assets cataloged, only nineteen are Experimental Setups that are assigned as projects in the Chemical Engineering Laboratory sequence. The purchase cost of those nineteen Experimental Setups was $573,622.00.

A total of five different categories were defined to classify the nineteen Experimental Setups that are assigned as projects in the Chemical Engineering Laboratory sequence. Each of the five different categories had at the least two different groups or options by which to categorize and at the most seven different groups or options by which to categorize. The primary findings based on these various categories include:

- Eight of the nineteen (42%) Experimental Setups have been installed within the past seven years.
- Fourteen of the nineteen (74%) Experimental Setups have been developed in-house.
- Twelve of the nineteen (63%) Experimental Setups are categorized as pilot scale while the remaining seven of the nineteen (37%) Experimental Setups are categorized as bench scale.
- The nineteen Experimental Setups that are assigned as projects provide good coverage of all major subject areas; the most covered subject area is mass transfer while the least covered subject area is thermodynamics.
- Eighteen of the nineteen (95%) Experimental Setups utilize local displays.
- Ten of the nineteen (53%) Experimental Setups utilize the DeltaV Historian platform.
- Five of the nineteen (26%) Experimental Setups have no existing data historization platform.

The project utilization during the last four academic years (AY 2013-14 to AY 2016-17) was analyzed. The primary findings of this analysis include:

- Nine of the nineteen Experimental Setups had a utilization of seventy percent (70%) or greater.
- The most utilized Experimental Setups at ninety-five percent (95%) were the Agitated Tank Experimental Setup and the Cooling Tower Experimental Setup.
- The Tangential Flow Filtration Experimental Setup has a utilization of zero percent (0%), which does not coincide well with the Experimental Setup having the second most expensive purchase cost; therefore, it is advised that the Tangential Flow Filtration Experimental Setup be brought to an operable condition so that it may be utilized in the

Chemical Engineering Laboratory. As mentioned earlier, multiple faculty members and students in the Chemical Engineering Department are collaborating to bring the Tangential Flow Filtration Experimental Setup into an operable condition.

The project mix between pilot scale and bench scale Experimental Setups for individual student assignments during the last four academic years (AY 2013-14 to AY 2016-17) was analyzed. The primary finding of this analysis includes:

- Fifty-three percent (53%) of Chemical Engineering students received a good balance between pilot scale and bench scale Experimental Setups, e.g., ideal pilot scale to bench scale ratios of two pilot scale Experimental Setups to three bench scale Experimental Setups (2:3) and three pilot scale Experimental Setups to two bench scale Experimental Setups (3:2).

All faculty in the Chemical Engineering Department were interviewed for ideas for new Experimental Setups and Analytical Instruments. A total of twenty-two laboratory additions or modifications were suggested and documented, two of which are currently in the process of being installed and implemented in the Chemical Engineering Laboratory.

The Experimental Setups within the Chemical Engineering Laboratory were compared to five other institutions. The primary findings include:

- Fifteen of the nineteen Experimental Setups have a corresponding equivalent at one or more institutions.
- Twenty-two Experimental Setups at other institutions did not have a corresponding equivalent at Rose-Hulman; however, six of those twenty-two Experimental Setups have a corresponding equivalent among the ideas for new Experimental Setups and Analytical Instruments proposed by faculty in the Chemical Engineering Department.

10.2 Recommendations

Based on the results in this work, the following recommendations can be made:

- Due to laboratory floor space limitations, future expansions should be focused on bench scale Experimental Setups and Analytical Instruments.
- The future of the Tangential Flow Filtration Experimental Setups has to be decided by the Chemical Engineering Department. The Experimental Setup should either be put into service soon or be decommissioned and replaced with another pilot scale Experimental Setup.
- Even though there is a good balance between individual subject areas, more Experimental Setups related to the subject area of thermodynamics can be added. Additionally, more Experimental Setups related to process control can be added in order to leverage the investment in the DeltaV system.
- As suggested by a faculty member, Ancillary/Supplemental options for control and data acquisition that have a greater degree of flexibility should be explored for Experimental Setups. These control and data acquisition options would not replace the DeltaV system, but would instead act as a safeguard if the DeltaV system became inoperable. Additionally, these ancillary/supplemental options for control and data acquisition would allow for Experimental Setups to be tested/implemented quickly before beginning the long process of configuring the DeltaV system for said Experimental Setups.
- As suggested by faculty members, improvements should be made to the Othmer Still Experimental Setup, Fuel Cell Experimental Setup, and Parr Reactor Experimental Setup. Improving these Experimental Setups will not only increase the longevity of the listed Experimental Setups, it will also allow for better control, data acquisition, and reliability

of the Experimental Setups, which will thereby increase the utility and learnability from the current Experimental Setups.

- Although the current project assignments provided a good balance between pilot scale and bench scale Experimental Setups, the experimental scale of project assignments should be monitored prior to making the assignments to ensure that Chemical Engineering students receive a good balance of pilot scale Experimental Setups and bench scale Experimental Setups.

11. FUTURE WORK

The analysis presented in this thesis focused primarily on the use of the assets within the Chemical Engineering Laboratory that are utilized in the Chemical Engineering Laboratory sequence, i.e., CHE 411/412/413. Similar analyses can be performed with respect to other courses and activities that utilize the assets within the Chemical Engineering Laboratory, such as EM 103 – Introduction to Design, CHE 540 – Advanced Process Control, and undergraduate and graduate research projects. The analysis of the laboratory projects assigned in the undergraduate laboratory courses (CHE 411/412/413) can be expanded to include the mix of subject areas that Chemical Engineering students experience on average. The comparison to other institutions can be expanded to include the specific use of the Experimental Setups, the specifics of the project assignments, and the educational objectives of the Chemical Engineering Laboratory sequence. The collected information in this thesis can be used as a stepping stone towards the development of a master plan for the improvement and renovation of the laboratory facilities in the next ten to fifteen years.

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APPENDICES

APPENDIX A: Spatial Properties of Assets (Ordered by Footprint – Experimental Setups Followed by Analytical Instruments)

Table A.1: Spatial Properties of Assets

Asset Name	Type	Experimental Scale	Footprint (ft^2)	Portability	Current Location
Fluid Flow	Experimental Setup	Pilot Scale	253.0	Set in Place	O-100
Filtration (Filter Press)	Experimental Setup	Pilot Scale	186.2	Set in Place	O-102
Saponification Reaction	Experimental Setup	Bench Scale	150.0	Portable	O-226
Tangential Flow Filtration	Experimental Setup	Pilot Scale	143.0	Set in Place	O-100
Cooling Tower	Experimental Setup	Bench Scale	143.0	Portable	O-100A
Corning Column	Experimental Setup	Pilot Scale	121.0	Set in Place	O-100
Multipass Heat Exchanger	Experimental Setup	Pilot Scale	119.0	Set in Place	O-100
Instrumentation and Control	Experimental Setup	Pilot Scale	110.0	Set in Place	O-102
Reverse Osmosis	Experimental Setup	Pilot Scale	99.0	Set in Place	O-100
Agitated Tank	Experimental Setup	Pilot Scale	98.9	Set in Place	O-102
Tubular Flow Reactor	Experimental Setup	Pilot Scale	98.0	Set in Place	O-100
Ultrafiltration	Experimental Setup	Bench Scale	90.0	Set in Place	O-202
Parr Reactor	Experimental Setup	Bench Scale	90.0	Set in Place	O-202
Pumps	Experimental Setup	Pilot Scale	84.0	Set in Place	O-102
Othmer Still	Experimental Setup	Bench Scale	75.0	Set in Place	O-102A
Fluidized Bed	Experimental Setup	Pilot Scale	72.0	Set in Place	O-102
Dryer	Experimental Setup	Pilot Scale	64.0	Set in Place	O-102
Fuel Cell	Experimental Setup	Bench Scale	40.0	Portable	O-102

Table A.1 Continued

Asset Name	Type	Experimental Scale	Footprint (ft^2)	Portability	Current Location
Drug Delivery	Experimental Setup	Bench Scale	30.0	Portable	O-200B
Fermenter	Analytical Instrument		30.0	Set in Place	O-226
Particle Analyzer	Analytical Instrument		21.0	Set in Place	O-102A
FTIR	Analytical Instrument		15.0	Set in Place	O-200B
UV Spectrometer	Analytical Instrument		15.0	Set in Place	O-200B
UV Spectrometer	Analytical Instrument		15.0	Set in Place	O-226
TGA	Analytical Instrument		7.5	Set in Place	O-200B
Platform Top Loading Balances	Analytical Instrument		6.0	Portable	O-102B
Solids Handling System	Analytical Instrument		6.0	Set in Place	O-102B
Forced Convection Oven	Analytical Instrument		5.0	Set in Place	O-102B
DSC	Analytical Instrument		5.0	Set in Place	O-200B
Small Instrument Autoclave	Analytical Instrument		4.0	Set in Place	O-226
Tensile Test Stretcher	Analytical Instrument		4.0	Set in Place	O-200B
Thin Film Polymer Lab	Analytical Instrument		4.0	Set in Place	O-200B
Vacuum Oven System	Analytical Instrument		4.0	Set in Place	O-226
Corrosion Studies Unit	Analytical Instrument		4.0	Set in Place	O-202
Vacuum Oven	Analytical Instrument		4.0	Set in Place	O-202
10 Ton Press	Analytical Instrument		4.0	Set in Place	O-202
Microwave Dryer	Analytical Instrument		4.0	Set in Place	O-102
Micro Balances	Analytical Instrument		3.8	Portable	O-102B
Density Meter	Analytical Instrument		3.0	Set in Place	O-102A
Cell Centrifuge	Analytical Instrument		2.0	Set in Place	O-226
Glucose Analyzer	Analytical Instrument		2.0	Set in Place	O-226

Table A.1 Continued

Asset Name	Type	Experimental Scale	Footprint (ft^2)	Portability	Current Location
Homogenizer	Analytical Instrument		2.0	Set in Place	O-226
Mini Centrifuge	Analytical Instrument		2.0	Set in Place	O-226
Mini Vortexer	Analytical Instrument		2.0	Set in Place	O-226
Spectronic 20D	Analytical Instrument		2.0	Set in Place	O-226
Inverted Microscope	Analytical Instrument		2.0	Portable	O-204
Drop Shape Analyzer	Analytical Instrument		2.0	Portable	O-202
Ultrapure Water System	Analytical Instrument		1.0	Portable	O-200B
pH Meter	Analytical Instrument		1.0	Portable	O-226
Temperature Bath	Analytical Instrument		1.0	Portable	O-226
Liquid Chromatography	Analytical Instrument		1.0	Set in Place	O-226
Micro Balance	Analytical Instrument		1.0	Portable	O-226
Microscope	Analytical Instrument		1.0	Portable	O-200B
Digital Scale	Analytical Instrument		1.0	Portable	O-102B
Top Loading Balances	Analytical Instrument		1.0	Portable	O-102B
pH Meter	Analytical Instrument		1.0	Portable	O-202
Micro Balance	Analytical Instrument		1.0	Portable	O-202
Temperature Bath	Analytical Instrument		1.0	Portable	O-204
Viscometer	Analytical Instrument		1.0	Portable	O-226
Viscometer	Analytical Instrument		1.0	Portable	O-226
pH Meters	Analytical Instrument		1.0	Portable	O-102A
Temperature Bath	Analytical Instrument		1.0	Portable	O-102A
O_2 Sensor	Analytical Instrument		0.0	Set in Place	O-202
Reactor Glassware	Analytical Instrument		0.0	Portable	O-204

Table A.1 Continued

Asset Name	Type	Experimental Scale	Footprint (ft^2)	Portability	Current Location
Tangential Flow Filtration Membrane	Analytical Instrument		0.0	Set in Place	O-100
Magnetic Stirrers	Analytical Instrument		0.0	Portable	O-102A
Refractometer	Analytical Instrument		0.0	Portable	O-102A

APPENDIX B: Purchase Cost, Year of Installation, and Utilization of Assets (Ordered by Purchase Cost – Experimental Setups Followed by Analytical Instruments)

Table B.1: Purchase Cost, Year of Installation, and Utilization of Assets

Asset Name	Purchase Cost	Source for Purchase Cost Information	Year of Installation	Utilization in CHE 411/412/413
Corning Column	$150,000.00	Banner Web	1983	63.64%
Tangential Flow Filtration	$94,622.00	Banner Web	1985	0.00%
Instrumentation and Control	$50,000.00	Banner Web	2006	70.45%
Fuel Cell	$42,000.00	Banner Web	2010	20.45%
Cooling Tower	$32,000.00	Banner Web	2012	95.45%
Tubular Flow Reactor	$25,000.00	Banner Web	2007	43.18%
Parr Reactor	$25,000.00	Banner Web	2013	29.73%
Filtration (Filter Press)	$22,000.00	Banner Web	1983	84.09%
Dryer	$22,000.00	Banner Web	1999	52.27%
Agitated Tank	$20,000.00	Banner Web	1988	95.45%
Fluid Flow	$18,000.00	Banner Web	1983	88.64%
Pumps	$18,000.00	Banner Web	2013	90.91%
Multipass Heat Exchanger	$15,000.00	Banner Web	2016	77.27%
Othmer Still	$12,000.00	Banner Web	1983	90.91%
Saponification Reaction	$8,000.00	Estimate	2006	59.09%
Fluidized Bed	$6,000.00	Estimate	2014	58.54%
Ultrafiltration	$5,000.00	Banner Web	2009	43.18%

Table B.1 Continued

Asset Name	Purchase Cost	Source for Purchase Cost Information	Year of Installation	Utilization in CHE 411/412/413
Reverse Osmosis	$5,000.00	Estimate	2015	50.00%
Drug Delivery	$4,000.00	Estimate	2016	54.55%
Particle Analyzer	$55,000.00	Banner Web	2008	
Fermenter	$39,809.00	Banner Web	2016	
Thin Film Polymer Lab	$25,000.00	Banner Web	2009	
Corrosion Studies Unit	$24,500.00	Banner Web	2009	
Density Meter	$22,000.00	Banner Web	2003	90.91%
Homogenizer	$20,000.00	Banner Web	1985	
DSC	$20,000.00	Banner Web	2009	
TGA	$20,000.00	Banner Web	2009	
Inverted Microscope	$19,983.00	Banner Web	2011	
Viscometer	$18,000.00	Banner Web	2009	
FTIR	$17,000.00	Banner Web	2004	
Drop Shape Analyzer	$17,000.00	Banner Web	2008	
Microwave Dryer	$15,000.00	Banner Web	2004	84.09%
Cell Centrifuge	$12,000.00	Banner Web	1985	
UV Spectrometer	$12,000.00	Banner Web	2004	54.55%
10 Ton Press	$12,000.00	Banner Web	1983	
Liquid Chromatography	$10,000.00	Banner Web	1985	
Viscometer	$8,600.00	Banner Web	2009	
Vacuum Oven System	$6,213.00	Banner Web	2011	
Platform Top Loading Balances	$5,400.00	Banner Web	2006	
Ultrapure Water System	$5,000.00	Banner Web	2011	

Table B.1 Continued

Asset Name	Purchase Cost	Source for Purchase Cost Information	Year of Installation	Utilization in CHE 411/412/413
Solids Handling System	$5,000.00	Banner Web	2005	
Tangential Flow Filtration Membrane	$5,000.00	Banner Web	2004	
Glucose Analyzer	$4,000.00	Banner Web	1991	
Top Loading Balances	$3,600.00	Banner Web	1983	
Tensile Test Stretcher	$3,000.00	Banner Web	2008	
Micro Balances	$3,000.00	Banner Web	1983	
Micro Balance	$3,000.00	Banner Web	1990	
pH Meters	$3,000.00	Banner Web	1995	
Temperature Bath	$2,700.00	Banner Web	2002	
Forced Convection Oven	$2,600.00	Banner Web	2006	52.27%
Micro Balance	$2,500.00	Banner Web	2002	
Refractometer	$2,500.00	Banner Web	1995	
Microscope	$2,000.00	Banner Web	1985	
Spectronic 20D	$2,000.00	Banner Web	1985	
O_2 Sensor	$2,000.00	Banner Web	2004	
Reactor Glassware	$2,000.00	Banner Web	1983	
Temperature Bath	$1,800.00	Banner Web	2009	
UV Spectrometer	$1,200.00	Banner Web	1985	
pH Meter	$1,000.00	Banner Web	1987	
Temperature Bath	$1,000.00	Banner Web	1983	
Small Instrument Autoclave	$1,000.00	Banner Web	1985	
Digital Scale	$1,000.00	Banner Web	2001	
pH Meter	$1,000.00	Banner Web	1987	

Table B.1 Continued

Asset Name	Purchase Cost	Source for Purchase Cost Information	Year of Installation	Utilization in CHE 411/412/413
Vacuum Oven	$1,000.00	Banner Web	1983	
Magnetic Stirrers	$1,000.00	Banner Web	1995	
Mini Centrifuge	$800.00	Banner Web	2005	
Mini Vortexer	$600.00	Banner Web	2005	

APPENDIX C: Dean's Current List of Equipment

Appendix C contains a copy of the Dean's Current List of Equipment that is available on Rose-Hulman's Banner Web. The Dean's Current List of Equipment documents assets on a per department basis in order to better track the purchase cost, year of purchase/installation, and condition of each asset. The assets documented for the Chemical Engineering Department in the Dean's Current List of Equipment were last updated in 2011; therefore, some of the information presented is obsolete and needs to be updated.

ROSE-HULMAN INSTITUTE OF TECHNOLOGY

Current Equipment List

Select Equipment from list

To edit or modify an existing equipment record, please select an entry from the table below by checking one (1) checkbox. **To create a new equipment record, click Continue without selecting a record.**

Be sure to use numeric characters only when specifying unit price.

	Department Code	Lab Name	Quantity	Description	Unit Cost	Category	Condition	Activity Date
☐	CHE	Biochemical Engineering L	1	2L Fermentor -- New Brunswick Scientific	$25,000.00		S - State of the Art	
☐	CHE	Biochemical Engineering L	1	Barnstead Nano-Pure UV/UF ultrapure water sys.	$5,000.00		S - State of the Art	
☐	CHE	Biochemical Engineering L	1	Beckman 71 PH meter	$1,000.00		A - Adequate	
☐	CHE	Biochemical Engineering L	1	Buchi 461 temperature bath	$1,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Cell Centrifuge (CEPA)	$12,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Glucose Analyzer	$4,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Homogeniser--APV	$20,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Liquid Cromatography--Pharmacia	$10,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Mettler AE240 Micro Balance	$2,500.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Microscope -- Olympus C011	$2,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Mini Centrifuge VWR	$800.00	A - Basic Instruction	M - Modern	
☐	CHE	Biochemical Engineering L	1	Mini Vortexer VWR	$600.00	A - Basic Instruction	M - Modern	
☐	CHE	Biochemical Engineering L	1	Small Instrument Autoclave	$1,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Spectronic 20D	$2,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Biochemical Engineering L	1	Tensile test stretcher	$3,000.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Biochemical Engineering L	1	Thin Film Polymer Lab	$25,000.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Biochemical Engineering L	1	Vacuum Oven System	$6,213.00	A - Basic Instruction	M - Modern	
				Micro Balances				

☐	CHE	Dry Instrument Lab	1	(Sartorius Suspension Scale160g max, Right-A-Weight suspension Scale 160g max)	$3,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Dry Instrument Lab	3	Platform Top Loading Metler Balances	$5,400.00	A - Basic Instruction	M - Modern	
☐	CHE	Dry Instrument Lab	1	Sartorius Digital Scale 6000g max	$1,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Dry Instrument Lab	1	Solid handling system	$5,000.00	A - Basic Instruction	M - Modern	
☐	CHE	Dry Instrument Lab	2	Top Loading Balances (Sartorius Top loading Scale 1000g max)	$3,600.00	A - Basic Instruction	A - Adequate	
☐	CHE	Dry Instrument Lab	1	VWR Forced Convection Oven	$2,600.00	A - Basic Instruction	S - State of the Art	
☐	CHE	Instrument Lab	1	FTIR Perkin-Elmer	$17,000.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Instrument Lab	1	Inverted Microscope	$19,983.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Instrument Lab	1	UV Spec, Lambda 35 with Dell PC	$12,000.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Kinetics Lab	1	Beckman 71 PH meter	$1,000.00	A - Basic Instruction	M - Modern	
☐	CHE	Kinetics Lab	1	Corrosion Studies Unit	$24,500.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Kinetics Lab	1	Illinois Instruments O2 Sensor	$2,000.00	B - Advanced Equipment	M - Modern	
☐	CHE	Kinetics Lab	1	Mettler AJ100 micro balance	$3,000.00	B - Advanced Equipment	M - Modern	
☐	CHE	Kinetics Lab	1	Parr Reactor-2lit	$25,000.00	A - Basic Instruction	M - Modern	
☐	CHE	Kinetics Lab	1	Polyscience Temperature Bath No.3	$2,700.00	A - Basic Instruction	M - Modern	
☐	CHE	Kinetics Lab	1	Vacuum oven -- Precision Scientific Co.	$1,000.00	A - Basic Instruction	A - Adequate	
☐	CHE	Macromolecular Lab	1	Brookfield Viscometer	$8,600.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Macromolecular Lab	1	Carver 10 Ton Press	$12,000.00	B - Advanced Equipment	A - Adequate	
☐	CHE	Macromolecular Lab	1	Drop Shape Analyzer	$17,000.00	B - Advanced Equipment	S - State of the Art	
☐	CHE	Macromolecular Lab	1	Killion Extruder	$25,000.00	B - Advanced Equipment	A - Adequate	

	CHE	Macromolecular Lab	1	Merlin Viscometer with Computer	$18,000.00	B - Advanced Equipment	S - State of the Art	
	CHE	Macromolecular Lab	1	Reactor Glassware	$2,000.00	A - Basic Instruction	A - Adequate	
	CHE	Polymer Measurements Lab	1	DSC -- TA Instruments	$20,000.00	B - Advanced Equipment	S - State of the Art	
	CHE	Polymer Measurements Lab	1	Dell Computer for DSC & TGA	$2,000.00	B - Advanced Equipment	S - State of the Art	
	CHE	Polymer Measurements Lab	1	TGA -- TA Instruments	$20,000.00	B - Advanced Equipment	S - State of the Art	
	CHE	Process Control Lab	1	DeltaV System (Development)	$21,584.00	B - Advanced Equipment	S - State of the Art	
	CHE	Process Control Lab	1	DeltaV System/Historian (Upgrade)	$56,731.00	B - Advanced Equipment	S - State of the Art	
	CHE	Special Projects Lab	1	20L Fermentation (Upgrade)	$39,809.00	B - Advanced Equipment	M - Modern	
	CHE	Special Projects Lab	1	Spectronic 21 uv	$1,200.00	A - Basic Instruction	A - Adequate	
	CHE	Special Projects Lab	1	TFF Membrane Filtration (Pellicon)	$5,000.00	B - Advanced Equipment	M - Modern	
	CHE	Unit Operations Lab	1	Absorber Column	$30,000.00	A - Basic Instruction	O - Obsolete	
	CHE	Unit Operations Lab	1	Agitated Tank Heat Exchanger	$20,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Concentric Tubes Heat Exchanger	$15,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Cooling Tower	$32,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	1	Corning Column Distillation	$150,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	2	Density Meter	$22,000.00	A - Basic Instruction	M - Modern	
	CHE	Unit Operations Lab	1	Fuel Cell Experiment (TVN)	$42,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	1	Karr Column	$50,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Liquid Flow Experiment	$18,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Liquid Level Control	$50,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	1	Micro filtration Experiment Ceraflow Ceramic (Upgrade)	$73,021.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	1	Microwave Dryer	$15,000.00	A - Basic Instruction	M - Modern	
	CHE	Unit Operations Lab	1	Multi-pass Heat Exchanger	$15,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Plate and Frame Filtration	$22,000.00	A - Basic Instruction	S - State of the Art	

	CHE	Unit Operations Lab	1	Process Control Simulation	$20,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Pumps Experiment	$18,000.00	A - Basic Instruction	A - Adequate	
	CHE	Unit Operations Lab	1	Rankin Cycler	$24,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Unit Operations Lab	1	Tangential Flow Filtration-TTF	$21,601.00	B - Advanced Equipment	S - State of the Art	
	CHE	Unit Operations Lab	1	Tray Dryer	$22,000.00	A - Basic Instruction	M - Modern	
	CHE	Unit Operations Lab	1	Tubular Flow Reactor	$25,000.00	A - Basic Instruction	S - State of the Art	
	CHE	Wet Instrument Lab	8	Magnetic Stirrers	$1,000.00	A - Basic Instruction	A - Adequate	
	CHE	Wet Instrument Lab	1	Mastersizer particle analyzer	$55,000.00	B - Advanced Equipment	S - State of the Art	
	CHE	Wet Instrument Lab	1	Othmer Still	$12,000.00	A - Basic Instruction	A - Adequate	
	CHE	Wet Instrument Lab	3	PH Meters	$3,000.00	A - Basic Instruction	A - Adequate	
	CHE	Wet Instrument Lab	1	Polyscience Temperature Bath No. 2	$1,800.00	A - Basic Instruction	A - Adequate	
	CHE	Wet Instrument Lab	1	Refractometer -- Leica Auto ABBE	$2,500.00	B - Advanced Equipment	A - Adequate	

APPENDIX D: Comparative Survey – Bucknell University

Bucknell University is located in Lewisburg, Pennsylvania and has an undergraduate enrollment of approximately 3,500 students [37]. The Chemical Engineering Department falls within the College of Engineering and in 2017, Bucknell University's engineering program was ranked by U.S. News & World Report as the seventh best undergraduate engineering program where a doctorate is not offered [37; 38].

Bucknell University's Chemical Engineering Department offers the following description of the Unit Operations Laboratory:

> "The Unit Operations Laboratory allows students to gain hands-on experience while studying both the fundamental principles and practical applications of chemical engineering. The laboratory includes pilot-plant scale equipment that represents unit operations (specific components common to a variety of chemical processes) found in industrial settings…
>
> This facility is specifically designed to introduce students to larger scale industrial processes commonly encountered by chemical engineers. In this laboratory, students work in teams to apply principles learned in the classroom to solve practical engineering problems" [46].

Projects/Experiments present within the laboratory include [46]:

- Staged Distillation Column
- Packed Distillation Column
- Counter-Current Heat Exchangers

- Ion Exchange Units
- Gas Absorption Column
- Liquid-Liquid Extraction Column
- Membrane Separators
- Spray Dryer
- Plate and Frame Filter Press

APPENDIX E: Comparative Survey – Cooper Union

The Cooper Union for the Advancement of Science and Art, commonly referred to as Cooper Union, is located in New York, New York and has an undergraduate enrollment of approximately nine hundred students [39]. The Chemical Engineering Department falls within the Albert Nerken School of Engineering and in 2017, Cooper Union's engineering program was ranked by U.S. News & World Report as the ninth best undergraduate engineering program where a doctorate is not offered [38; 39].

Cooper Union's Chemical Engineering Department offers the following description of the Unit Operations Laboratory:

> "The Unit Operations Laboratory provides chemical engineering students the opportunity to observe, analyze and apply their engineering knowledge and training to the operation of equipment and processes commonly found in many chemical industries…
>
> Throughout their undergraduate education at The Cooper Union, students are exposed to various unit operations in their coursework. During their senior year, students take a two-semester laboratory sequence in which they are given hands-on exposure to ten different unit operations. This complements their training as chemical engineers and provides intensive experiences in rigorous experimental approaches, analysis and safe operating procedures. Currently, the following unit operations are being studied:
>
> Fall Semester:
>
> - Filtration

- Flooding Point of a Packed Column
- Fluid Flow
- Heat Exchanger
- Reactors

Spring Semester:

- Distillation
- Drying
- Liquid-Liquid Extraction
- Membrane Air Separation
- Reverse Osmosis

In addition to performing experiments that illustrate the above unit operations, the students receive extensive training in technical and communication skills. Students are required to write laboratory reports on a scholarly level, prepare and present posters, write executive memorandums and funding proposals, and give technical oral presentations" [47].

APPENDIX F: Comparative Survey – Michigan Technological University

Michigan Technological University is located in Houghton, Michigan and has an undergraduate enrollment of approximately 5,750 students [40]. The Chemical Engineering Department falls within the College of Engineering and in 2017, Michigan Technological University's engineering program was ranked by U.S. News & World Report as the sixty-third best undergraduate engineering program where a doctorate is offered [40; 44].

Michigan Technological University's Chemical Engineering Department offers the following description of the Unit Operations Laboratory:

> "The Department of Chemical Engineering offers students a unique learning experience with its world-class Unit Operations Laboratory and Process Simulation and Control Center (PSCC), which boasts 6,500 square feet and a three-story open bay dedicated to chemical-processing education.
>
> The laboratory features 18 bench and pilot-plant-scale unit-operations experiments focused on pumping fundamentals, heat exchange, membrane separation, kinetics, liquid extraction, vacuum drying, and flow measurement, among other chemical processes. Students gain hands-on experience with two fully automated pilot plants: a three-story distillation column (solvent recovery unit) and a two-story batch reactor. The PSCC is equipped with a DeltaV control system and OSI Soft-PIdata historian and retrieval software.
>
> This unique facility affords students the opportunity to learn in a real-world chemical-processing work environment providing a practical, hands-on experience. Two exciting

capstone courses for chemical engineering seniors are based on the lab; these courses allow students to build teamwork skills in a state-of-the-art learning complex. Process safety is emphasized in the laboratory" [41].

Projects/Experiments present within the laboratory include [42]:

- Solvent Recovery
- Polymerization Reactor
- Flow Measurement and Control
- Shell and Tube Heat Exchanger
- Cooling Tower
- Vacuum Drying
- Plate and Frame Filter Press
- Liquid-Liquid Extraction
- Simulations
- Centrifugal Pumping with AC Drive
- Capillary Viscometer
- Fixed Bed Reactor
- Fluidization
- Membrane Separation
- Centrifugal Pumping with DC Drive

APPENDIX G: Comparative Survey – Purdue University

Purdue University is located in West Lafayette, Indiana and has an undergraduate enrollment of approximately 29,500 students [43]. The Chemical Engineering Department falls within the College of Engineering and in 2017, Purdue University's engineering program was ranked by U.S. News & World Report as the ninth best undergraduate engineering program where a doctorate is offered [43; 44].

Purdue University's Chemical Engineering Department offers the following description of the Unit Operations Laboratory:

> "The Alan H. Fox Unit Operations Laboratory now provides an appropriate setting for seniors in chemical engineering to sharpen their skills and apply the theoretical training gained in the classroom. Advanced undergraduate students investigate open-ended chemical engineering design projects and engage in creative problem-solving and decision-making activities. In this laboratory, seniors develop their scale-up, process design, experimental design, data analysis and testing skills, as well as experience working in diverse teams and reporting their results orally and in written form" [48].

Projects/Experiments present within the laboratory include [48]:

- Sieve-Tray Fractional Distillation
- Liquid-Liquid Extraction
- Flash Vaporizer
- Gas-Liquid Absorption
- Membrane Oxygen Separation from Air

- Ion Exchange Recovery of Salts from Dilute Solutions
- Polymerization Process
- Bench Scale Packed Bed Catalytic Reactor
- Immobilized Enzyme Reactor
- Soluble Enzymatic Reactor
- Tray Dryer
- Water Cooling Tower
- Crystallization Process

APPENDIX H: Comparative Survey – Rowan University

Rowan University is located in Glassboro, New Jersey and has an undergraduate enrollment of approximately 13,250 students [45]. The Chemical Engineering Department falls within the Henry M. Rowan College of Engineering and in 2017, Rowan University's engineering program was ranked by U.S. News & World Report as the twenty-second best undergraduate engineering program where a doctorate is not offered [38; 45].

The Department of Chemical Engineering at Rowan University has established the following objectives for the Unit Operations Laboratory:

1. "Understand and apply engineering experimentation techniques and safety procedures common to the chemical industry.
2. Apply principles developed in chemical engineering courses to the analysis of chemical engineering processes and unit operations.
3. Improve skills of technical writing.
4. Improve skills necessary for group work – interpersonal skills, coordination of the efforts of several persons, leader and subordinate roles, etc." [49].

Projects/Experiments present within the laboratory include [50]:

- Liquid-Liquid Extraction
- Fluidized Bed
- Ultrafiltration/Microfiltration
- Electrodialysis Membrane System
- HPLC

- Catalytic Reactor System with FTIR
- CSTR System
- Packed Columns for Gas-Liquid Absorption
- Shell and Tube Heat Exchanger
- Climbing Film Evaporator
- Multiphase Mixing
- Reverse Osmosis
- Pervaporation Membrane System
- Fermentation
- Tubular Flow System
- Specialty Chemical Pilot Plant
- Distillation Column