SOYBEANS TO CHEMICALS: A CASE STUDY FOR UNDERGRADUATE CHEMICAL ENGINEERING EDUCATION

by
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A thesis committed to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

Oxford
May 2018

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ABSTRACT

The aim of this thesis is to develop a case study to reinforce the concepts that are required knowledge for chemical engineers in their sophomore year of curriculum, continuing through all of their education. The process that will be examined is the production of soybean oil, protein powder, and succinic acid from the harvest of soybeans. Further, this process will be used to align with the objectives of the chapters from the required textbook for the material balances class. The soybean industry is one of the largest in the United States agricultural sector, so it is an important real-world example for young engineers to evaluate. The process itself and its relevance will be discussed in the following.

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I. Introduction

The foundations of the chemical engineering curriculum are the material and energy balance classes taught in the sophomore year. All other concepts taught throughout the chemical engineering undergraduate degree program hinge upon the principles learned there. A key component of the transition in student skills is solving a case study. The case study helps the students to see, for the first time, what an entire chemical process looks like and the types of calculations involved in its analysis. I therefore undertook for my thesis to create a process that would not only adequately develop the material balance principles but would also introduce the themes that become relevant in later classes. This thesis represents the material balances portion of a case study that for years to come will test the students' ability to fully understand and apply what they must know to be a successful chemical engineer.

The process through which I chose to teach these principles is that of a hypothetical soybean processing plant in which three different products are made: soybean oil, soy protein powder, and succinic acid. Due to the formation of multiple products, the process contains a wide variety of unit operations that will help to not only teach material balances, but also introduce ideas from future classes such as Separation Processes, Engineering Economics, Reactor Design, and Fluid Dynamics. Additionally, students will be expected to apply concepts that they have already learned in freshman level courses, particularly the general chemistry courses.

A secondary use of the material balances case study is to introduce young chemical engineers to the diversity of the market. Each of the products being made in this process—succinic acid, protein powder, and soybean oil—may be found in most households in various forms, and it is important for the students to realize how much goes into even the simplest item. An in-depth examination of the three products and their uses will be given in Section III. This case study shows that chemical engineers may find employment in a wide variety of industries. Learning about different processes and career paths that are possible after graduating can encourage young engineers to continue working towards the degree.

II. Concepts

The main text that is used in the University of Mississippi's material balances class is *Elementary Principles of Chemical Processes* by Richard M. Felder, Ronald W. Rousseau, and Lisa G. Bullard (Ed. 4). Within this book, three chapters are the primary content used for the material balances classes, each of which introduces a different set of related concepts that will be used as building blocks for later chemical engineering classes. These concepts are primarily taught in an active learning style, meaning that students must actively engage and solve problems as part of in-class learning. The case study that the sophomore class must complete is designed to address the given set of concepts and challenge students to apply them critically outside of the classroom.

The first chapter taught in the material balances class is Chapter 4 (the content of chapters 2 and 3 are assumed to have been mastered in the freshmen introductory course), which teaches the fundamentals of material balances themselves. The learning objectives for this chapter are given in Appendix 1. Material balances are based on the law of conservation of mass, meaning that the mass flowing into a system should be equivalent to that of the mass flowing out of the system, assuming there is no accumulation or losses. This may be shown in equation form as:

$$\textit{input} + \textit{generation} - \textit{output} - \textit{consumption} = \textit{accumulation} \tag{1}$$

This concept is the basis for the course, and may be utilized to develop systems of equations that can solve the material flows within a single unit operation, set of unit operations, or an entire process, including systems that may involve reactions. Mastery of these concepts are of the utmost importance in becoming a chemical engineer, and are thus the focus in the solving of the case study. Further discussion of how to solve material balances is given in Section V.

The main problem posed within the case study is to solve the material balances for all streams in the entire processing plant; therefore, students must thoroughly understand the concepts of Chapters 2 through 4 to complete the bulk of the case study.

Comprehension of how to correctly work with reactive systems in particular will be important, as they apply the stoichiometry learned in general chemistry and begin to use concepts of a molar flow rate and the ability to appropriately convert between molar and mass flow rates. Terms that students will be expected to understand and be able to differentiate include batch, semi-batch, continuous, transient, and steady-state systems, all of which are vital for future understanding of varied chemical engineering academic concepts and industrial processes.

The case study in question deals with a continuous process that includes batch reactors functioning within a continuous system. This situation occurs commonly in industry, where batch processes are involved in continuous processes, and thus introduces the students to the complications that arise in these systems. Additionally, this chapter teaches students how to analyze systems containing recycles and bypasses. These types of system reroutes are important to understand, as they are used frequently in industry to maintain the cost and efficiency of a process and to regulate compositions in reactive systems. Although not used directly in the case study, similar methods have to be used to solve certain parts of the system. Chapter 4 also deals with dimensional analysis, which will be incredibly important for the case study at hand. It will also require students to work almost exclusively with the English system of units. Although metric units are usually used in engineering studies, the reality is that most industries in the United States still utilize English units. It is therefore very important that these students learn how to effectively use these units and convert between the two using dimensional analysis. With this long list of concepts, Chapter 4 becomes the main building block upon which all other understanding of chemical engineering stems.

The second chapter that is evaluated in the material balances class and is used in the case study is Chapter 5, the study of single-phase systems, meaning that there is only one state of matter within the process. A full list of chapter objectives is shown in Appendix 2. One of the main purposes of this chapter is to understand physically what is occurring with a system's components, as well as how to find relevant values within tabulated data and graphs. For example, students must learn how to read a steam table, which gives the specific volume, specific internal energy, and specific heat of steam at varying temperatures and pressures. From these tables, students can take these tabulated values and apply them to equations that will help explain the system. Students must also learn how to read graphs, such as the generalized compressibility charts that give the compressibility factor based on a fluid's reduced temperature and reduced pressure. With these values, the students can evaluate what is happening in the actual system, then can relate them to a standard value and compare different types of processes. This skill is addressed in objective **D** in the appendix. A valuable skill developed with the use of tabulated data and needed in the case study is that of interpolation, which is valuable for engineers that often refer to tables. Each parameter of the system can also be evaluated using equations of state, which are briefly introduced in this chapter. Equations of state will be examined more in-depth in the junior Multicomponent Thermodynamics class, but a base-level knowledge at this point is important to examine the incompressibility of a process and what this means. Compressibility, or a fluid's ability to change density based on changes in temperature or pressure, will be briefly evaluated in the case study, and this addresses objective **F** from the book. This chapter is much shorter than the previous chapter; therefore, less time is spent studying it and solving problems for the case study. However, it is important that it is fully understood.

Chapter 6 is the final chapter that is studied in the material balances class, and it evaluates multiphase systems, which means that there will be more than one state of matter existing in the process. The learning objectives for this chapter are listed in Appendix 3. One of the main points of multiphase systems is learning how they can be separated, and there are several methods that are discussed. Examples of such methods are listed in **A** of the learning objectives. These processes will be discussed further in the junior Separations class, so for the purpose of the case study, only a few of these separation processes will be relevant, particularly filtration and crystallization. Also, students must learn how to find the vapor pressure of a process using different methods, and they will again be expected to understand how to draw relevant data from a table. Related to these vapor pressures, they will also be expected to learn how to find the bubble point, boiling point, dew point, and other relevant information of a multiphase system. They will also be introduced to the natural separation of a system into two different phases based on its physical parameters. These concepts won’t be as relevant for the specific system that is being solved for the case study, but they draw on general chemistry concepts and future classes.

III. Industrial Relevance

Soybeans have become a remarkably useful crop in the last few decades, now accounting for approximately $15 billion in the American agriculture industry annually (“Soy Processing Fact Sheet”). The United States is the leading producer of soybeans in the world and the second largest exporter. These soybeans account for approximately 90% of the U.S. oilseed production. This oil is the second most widely used vegetable oil in the U.S. (“Soybeans and Oil Crops”). Typically, soybeans are separated into only two products—the aforementioned oil and the soybean meal (the remaining solids). The meal, consisting primarily of the proteins and carbohydrates contained within the beans, accounts for the largest source of animal protein feed. For our process, however, this meal will be separated into its individual components to form two distinct value-added products. Each of these products and their varied uses will be explored below.

Soybean oil is used widely in the food industry as the most common edible oil. It is desirable for cooking applications because of its high smoke point, which means it will degrade at a higher temperature, making it attractive for a wider range of cooking methods (Wolke). Most oils sold in stores that are marked as vegetable oil are soybean oil, as about 21 billion pounds of soybean oil are produced each year. The next highest vegetable oil production, canola oil, is less than one third that of soybean oil at 6 billion pounds per year (“All About Soyfoods”). Soybean oil, and vegetable oils in general, are regarded to be fairly healthy if consumed in their pure form. In fact, new studies show that soybean oil, when consumed in moderate amounts, can actually act to boost heart health as well as prevent other types of disease, such as Alzheimer's ("5 Amazing Benefits"). However, there is evidence that if the oil is further processed to be partially or fully hydrogenated, it forms trans-unsaturated fatty acids (trans fats), which have been linked to cardiovascular issues. Hydrogenation is a process by which hydrogen is added to an oil to solidify it ("Hydrogenated"). These hydrogenated oils are desirable because of their increased shelf life and flavor stability, but this may increase the risk of health issues if consumed too frequently. Liquid soybean oil is also known to have better emulsifying abilities than other vegetable oils, so it is typically a good choice to use soybean oil in its pure liquid form if possible.

The soy proteins will be separated and dried into protein powder, which is used widely as a food product, or can even be used for industrial purposes, such as adhesives. Protein powder in general has increased in popularity recently due to its perceived nutritional value and use by those in the exercise and health professions. According to Livestrong, "Soy is the only plant-based protein source that provides the body with all essential amino acids, making it a complete protein." Because of this, it is a popular choice for protein for those who are vegans and vegetarians who are looking for a non-animal route to get their necessary protein. In addition to being used for its health benefits, soy protein is used in other foods, such as baked goods and beverages to improve quality and stability ("The Benefits of Soybean Oil").

The carbohydrates, once isolated from the oil and proteins, are reacted with bacterial catalysts to form succinic acid, which is produced as a crystalline product. This acid is used throughout various industries, as it is very versatile, useful both in the clothing industry to make polymers and the pharmaceutical industry in pain relievers. (“Succinic Acid”). Additionally, it is mixed with surfactants in detergent and is often utilized in the food and beverage industry as a flavor additive and acid regulator. Succinic acid is not always made during soybean processing; in fact, it is actually typically produced from petroleum feedstock (Vaswani). This synthetic production of succinic acid is usually derived from maleic acid or its anhydride form (Almqvist). However, this method is expensive and can be dangerous to the environment, so an alternative production method is desirable. In total, succinic acid production has reached about 30,000 tonnes per year, with that figure increasing yearly.

Each of these products has multiple industry uses, which is what makes their production potentially valuable. They can be further refined or chemically modified to create other products if needed for another use. Given their importance, soybeans have been taxed in the past to impact the political realm. Different forms of soybean products were included in the United States’ negotiations between multiple countries during the Dillon Round of the General Agreement on Tariffs and Trade, including those between Canada, Japan, and the European Economic Community (“GATT Bilateral Negotiating”). More recently, China has threatened to place a tariff on the import of soybeans from the United States, among other imports, which would significantly affect the American soybean industry (Chandran). The political importance of such a large crop is yet another way to show students studying this project that there can be substantial ramifications for any industry, including one that isn’t likely considered to be one of the largest.

IV. Process Description

A simple, block flow diagram of the process is shown below in Figure 4.1, with a more detailed process description following.

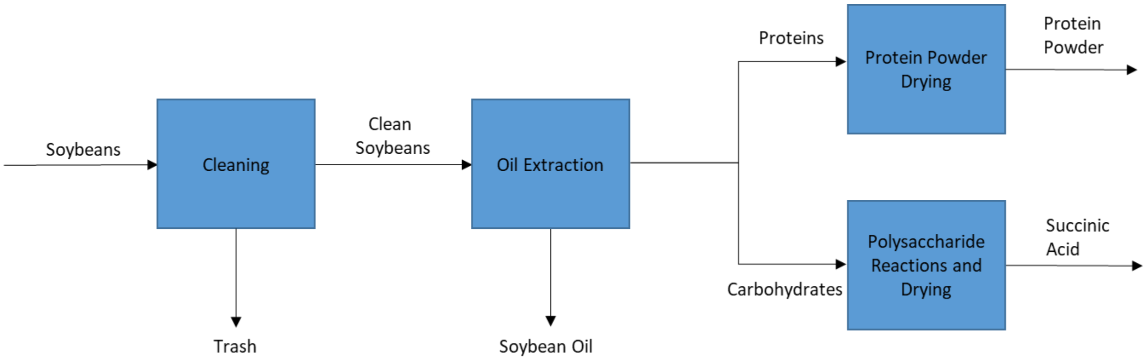


Figure 4.1: A Basic Overview of the Soybean Process

Once the soybeans are harvested from the field, they are sent into a cleaning process in which the dirt and trash that were collected along with the soybeans are removed. The clean beans are then sent into a dryer in which some of the water from the beans is removed. Next, the beans are sent through an aspirator where air is sent over the beans and the hulls are removed. These hulls can then be sent to a furnace where they are burned as fuel.

Now that there are only beans in the process, the process of extracting and forming products can start. First, the beans are sent through an extruder where they are pressed to remove most of the oil. In this context, an extruder acts simply as a press that pushes the fluid through openings only large enough to extract the pure oil. This oil can be used as is, or it can be further processed, depending on its intended use (refer to Section III). The stream containing the pressed beans is then split and sent into duel extractors, where hot water is added to dissolve the soluble carbohydrates based on their solubilities, a concept addressed in objective **M** of Appendix 3. Typically extractors will utilize a residence time based on the amount of time it takes for the desired percentage of solute to go into solvent. It is also unlikely that 100% of the soluble carbohydrates would go into solution, but for the purpose of the case study, it is assumed this is a continuous process with complete extraction to ease calculations. There are also some insoluble carbohydrates in the beans which will become part of the protein powder product (see components in Appendix 5). The process flow diagram of this section of the process is shown below in Figure 4.2:

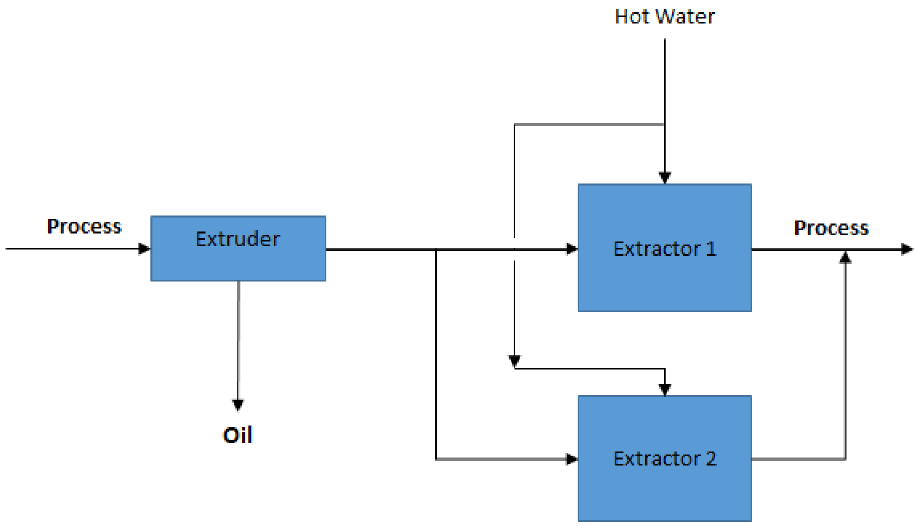


Figure 4.2: Extraction of Oil and Carbohydrates into Solution

Once the carbohydrates are in solution, the slurry is centrifuged to separate the stream into a liquid stream and a wet solids stream. The majority of the solution is sent further downstream, while a percentage remains part of the protein slurry. The protein slurry is mixed with wash water, which removes the adhering carbohydrate solution to join the carbohydrate solution stream. Meanwhile, the protein powder slurry is dried by direct injection with superheated steam and is sent off as a final protein powder product.

Superheated steam is sometimes used in industry to dry a process by vaporizing water in the system without actually condensing the steam, so this method is just another way to introduce students to different tricks that are used in industry but may not necessarily be studied in class. The concept of a superheated vapor itself addresses objective **E** for Chapter 6. This section of the process is shown in Figure 4.3.

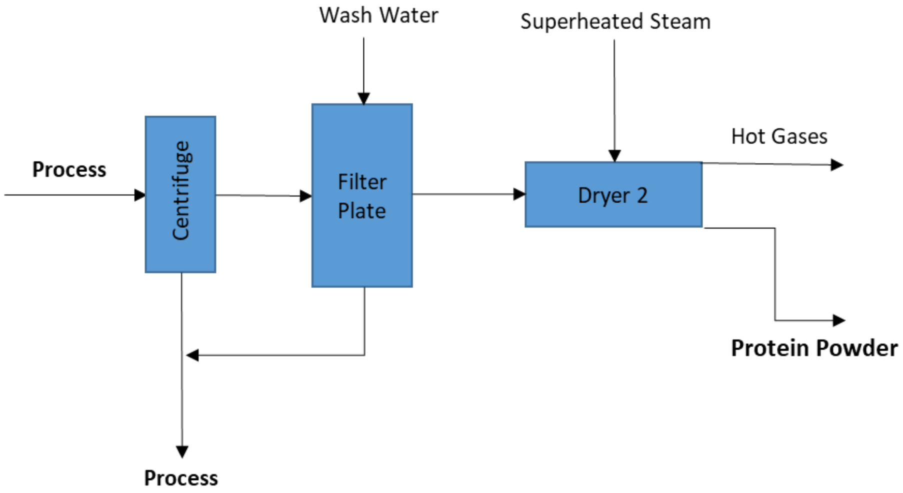


Figure 4.3: Separation of Final Protein Product and Carbohydrates

The carbohydrate solution is sent into a heat exchanger to adjust the temperature for the first reactor to one that is ideal for the reaction. It is then sent into a batch reactor system where the polysaccharides are bacterially broken down into monosaccharides. The hydrolysis reactions for the various complex sugars are given below:

Rxn 1 $C_{12}H_{22}O_{11} + H_2O \rightarrow 2\ C_6H_{12}O_6$

sucrose glucose+fructose

Rxn 2 $C_{18}H_{32}O_{16} + 2\ H_2O \rightarrow 3\ C_6H_{12}O_6$

raffinose glucose+fructose+ galactose

Rxn 3 $C_{24}H_{42}O_{21} + 3\ H_2O \rightarrow 4\ C_6H_{12}O_6$

stachyose glucose+fructose+ 2 galactose

Multiple reactors are needed to allow the batch unit operation to feed the continuous, steady-state process. The number of reactors used accounts for the time needed to ferment the bacteria and grow them to the desired concentration, fill the reactor with the process stream up to the desired volume, react, then empty and clean the reactor. The mixture of monosaccharide solution and bacteria are then sent to a filter where a cake of bacteria as well as the remaining soybean oil are removed from the process. This first reactor section is shown in Figure 4.4.

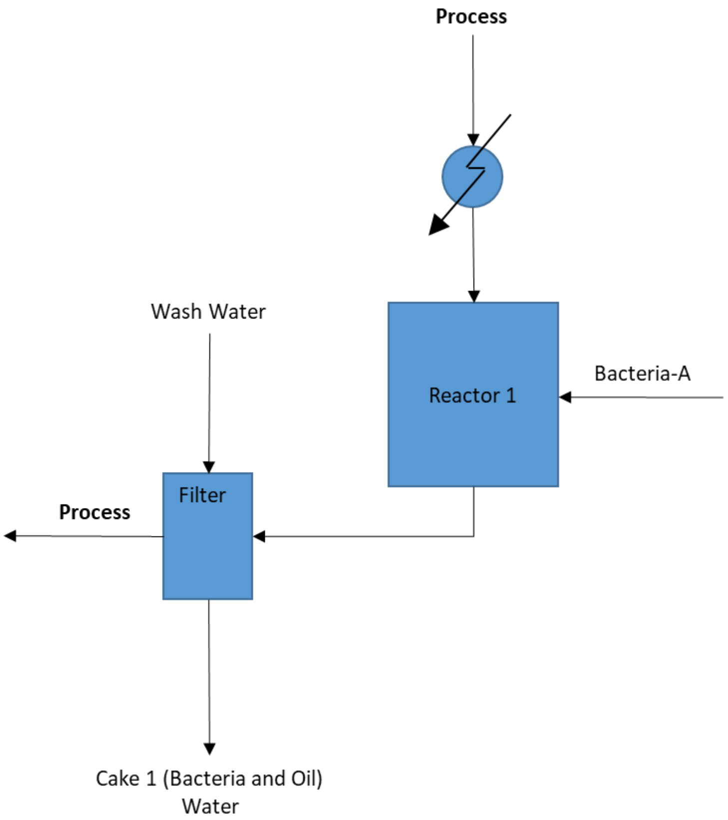


Figure 4.4: First Reactor Section and Bacterial Filtration

The stream now consists of only aqueous monosaccharides which may now be used to manufacture succinic acid. The stream is sent into the second reactor section where multiple batch reactors are again needed. A different bacteria is added to these reactors, where they are first allowed to multiply, then the bacteria break down the monosaccharides and produce succinic acid. The reaction breaks down the monosaccharides into succinic acid as well as a stoichiometric amount of water and acetylene (an off-gas). This reaction is shown below:

Rxn 4 $C_6H_{12}O_6 \rightarrow \underbrace{C_4H_6O_4}_{\text{succinic acid}} + 2\ H_2O + \underbrace{C_2H_2}_{\text{acetylene}}$

Once this reaction has reached completion, everything is removed from the reactor, which must then be cleaned before the next reaction cycle. The process stream is passed through a filter where a wet cake of bacteria is removed. This section is illustrated below in Figure 4.5.

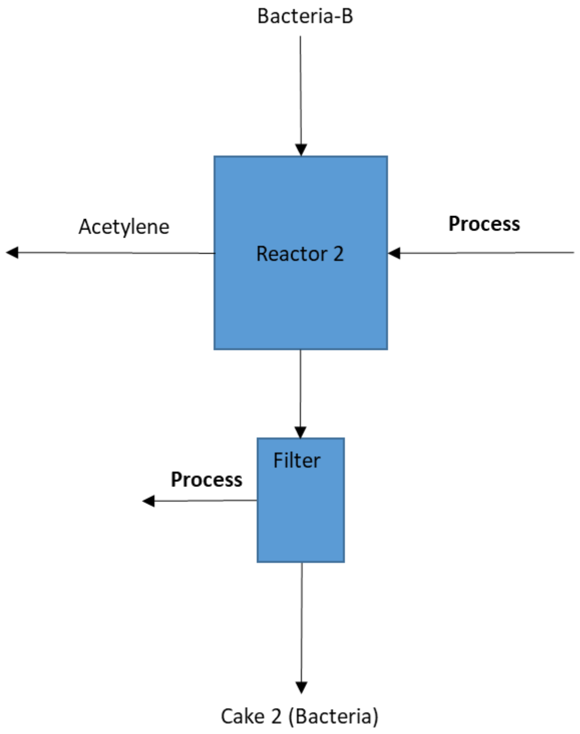


Figure 4.5: Second Reactor Section and Bacterial Filtration

The succinic acid solution can then be sent into a precipitator where sulfuric acid is added to decrease the pH of the solution, therefore greatly lowering the solubility. With a lower solubility, the succinic acid precipitates out of solution and crystallizes, a form of separation addressed in objective **A** from Appendix 3. The solid succinic acid is filtered and rinsed, then dried to its final solid state, where it can be packaged and sold. A diagram of this more complicated section of the process is shown in Figure 4.6.

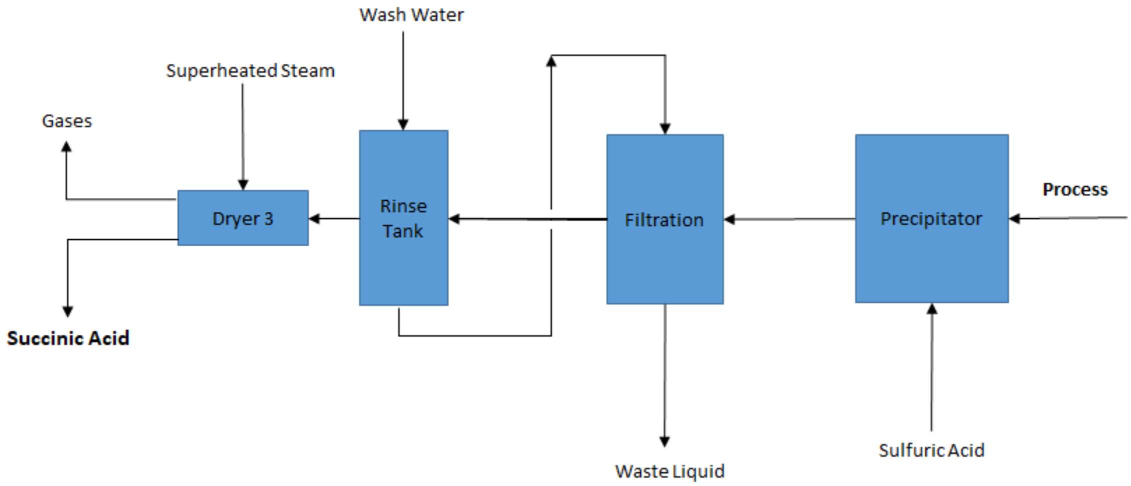


Figure 4.6: Crystallization and Drying of Final Succinic Acid Product

V. Material Balances

As discussed previously, a key goal of the case study is ensuring that students fully understand how to solve material balances for a full system. There will be questions following that teach other chemical engineering concepts. However, to be a successful chemical engineer, they must first be able to solve material balances with ease.

The best way to start solving a material balance, as taught in the class, is to first determine the process boundaries of the system. There are multiple boundaries that can be defined for a given system. An example of a system with multiple boundary definitions is shown in Figure 5.1.

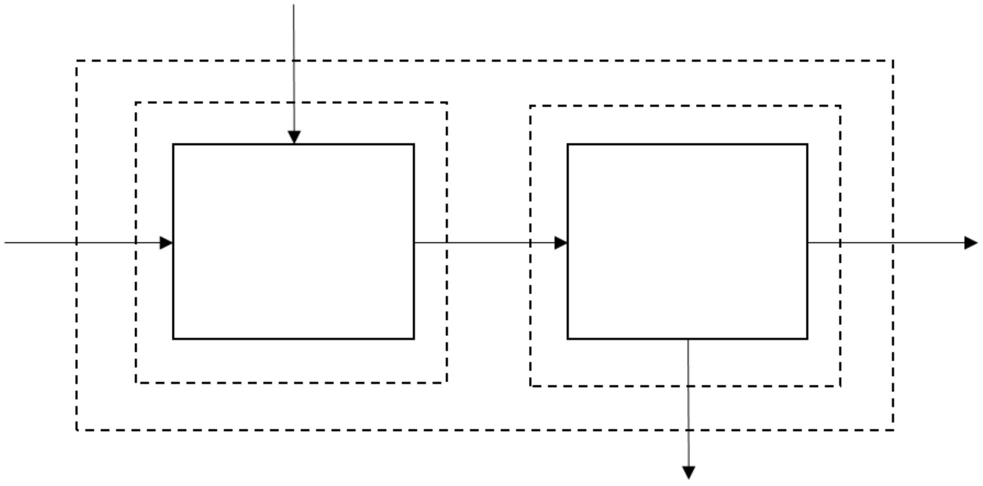


Figure 5.1: A General Material Balance Diagram with Multiple Process Boundaries

Once the involved process units have been defined, the student next determines the inlet and outlet streams of the system. As stated in the conceptual section, the sum of the mass of the inlet streams must equal the sum of the mass of the outlet streams, assuming there is no accumulation or “leaks”. For the sake of this case study, it is assumed that there are no leaks and no accumulation. The next step is to determine what is known about the system and what unknowns are needed for the system. All unknowns should be assigned a variable. Using each of these parameters, balance equations can be formed that explain the movement of mass through the system. A diagram showing a basic example of a process is given in Figure 5.2. Note that the control volume is indicated by the dashed lines around the process.

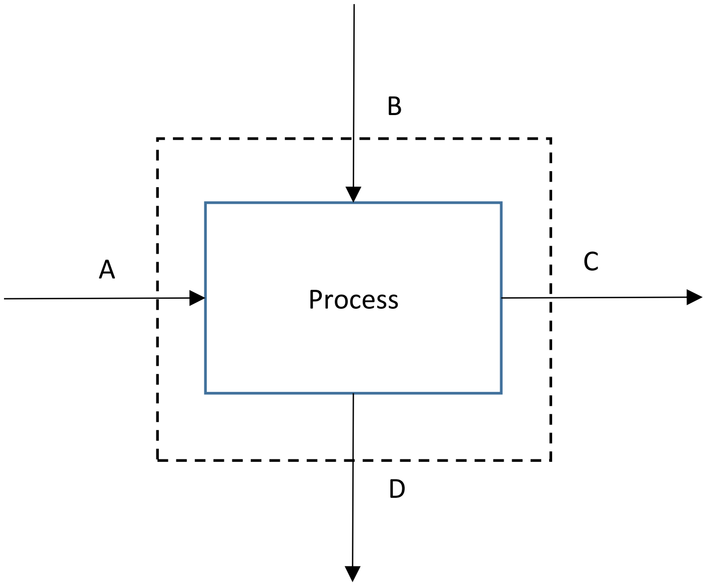


Figure 5.2: A General Material Balance with Named Streams

The first equation that should be written for the control volume is an overall mass balance. This simply relates the mass into and out of the system and sets the inlets and outlets equal to one another. In Figure 5.2, the inlet streams are A and B, and the outlet streams are C and D, as can be seen by the arrows pointing into and out of the control volume. Therefore, the overall mass balance should be written:

$$A + B = C + D \tag{2}$$

Additionally, individual mass balance equations can be written for each component within the system based on the mass fractions of each component. For example, assuming the system above contains only components M and N, the mass balance for component M would be:

$$x_{M,A}A + x_{M,B}B = x_{M,C}C + x_{M,D}D, \quad (3)$$

where $x_{M,A}$ represents the mass fraction of component M in stream A. Similarly, the mass balance for component N would look like:

$$x_{N,A}A + x_{N,B}B = x_{N,C}C + x_{N,D}D \quad (4)$$

Using all three of these equations, any unknowns of the systems should be able to be solved.

Whether or not the system can be solved using these equations can be determined using a degrees of freedom analysis, which is a part of both objectives **A** and **B** in Appendix 1. To do this, determine the number of unknowns in the system and the number of unique equations that can be written. Subtract the number of equations from the number of unknowns to determine the number of degrees of freedom. Ideally, there should be zero degrees of freedom, meaning that the system is solvable. If there is a negative degree of freedom, the process is over-specified. If it is positive, it is under-specified. Under- and over-specified systems are still solvable, but some additional means of solving may be necessary. If possible, the system should be taken to a point where it is well-defined so that it can be solved as a system of linear equations.

Within the case study that is being solved, it may be necessary to solve mass balances around each individual unit operation, or multiple operations may need to be grouped together. This is addressed in objective **A** for Chapter 4. Certain questions will also require a mass balance around the entire process. It is important to note that these balances only work for mass through a process. It is never advisable to do a volume balance, even if it may be possible for some systems. Mole balances are possible, but moles through a system don’t necessarily remain constant if there is a reaction taking place. If there is a reaction, moles must be accounted for based on the stoichiometry of the reaction. For any given system, an elemental balance can always be performed, although it may not always be the best method. An elemental balance uses the law that there cannot be spontaneous generation of individual elements within a system, so the flowrates of each individual element will stay constant. For example, if methane combusts by the reaction

Rxn 5 $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$,

the number of carbons through the system will always remain the same, even though it reacts to be a part of carbon dioxide instead of methane. Elemental balances may be used for certain parts of this case study, but they are not necessary. In general, it is advisable to use mass balances unless a reaction takes place. Some mole balances and stoichiometric changes will be important in the given case study.

VI. Questions

In addition to covering the concepts necessary to successfully complete material balances, questions have been added to introduce the concepts that are necessary for later classes in the chemical engineering curriculum. The questions and their relevance will each be presented and discussed below. See Appendix 5 for full assignment that is given to students. As this case study will be used for future classes, the solved material balances and questions will not be provided with this thesis to prevent unethical behavior from future students. Instead, the step-by-step solutions will only be provided to the professor.

For the first segment of the assignment, students are expected to present a team charter, a commitment to ethical behavior, and a process flow diagram of the process as it is described. The team charter is meant to not only acquaint the members of the team, but also to ensure that they know what to expect working together. The charter gives them a first place to start their conflict resolution should issues arise within the group while working through the project. The commitment to ethical behavior is meant to be one of the first times that these rising chemical engineers will be forced to consider what is expected in a professional environment from an engineer. Although this commitment relates more to a pledge against cheating, plagiarism, or similar measures, it helps to make students think about the code of ethics that will become increasingly important throughout their career as an engineer. The National Society of Professional Engineers provides a specific code of ethics to which all professional engineers must adhere, and it is important that engineers aspiring for this designation understand what is expected of them. This full code of ethics is shown in Appendix 4.

The students will also be required to draw a process flow diagram (PFD), which is an introduction to looking at a full process at a top-level view and addresses objective **B** from Chapter 4. It is their first exposure to the conversion of a process description into a PFD. This is the most important first step that is taken to continue looking at material balances. In order to understand how to perform the calculations for the process, it is crucial to first understand what is going on within the process. A PFD will almost always be the best place to start for figuring out a process, so it is important that students know how to convert a process that is described in words into an accurate process picture. It then becomes much easier to figure out what needs to be calculated within the process. The full PFD for the proposed soybean system is shown in Appendix 6, and it will be given to the students after they have attempted to draw their own PFD in the first assignment.

The second segment of this case study starts to introduce some of the more complicated concepts that a chemical engineer must know. First, some of the basic concepts from the engineering economics class are introduced. The production rates are used to figure out what the economic potential of the plant would be if the process were considered to be ideal, in the sense that everything would be completely converted and there was perfect recovery of every product. To solve this, a simple mass balance is performed around the system as a whole to determine where each component of the soybean goes. Then students will have to convert from the English unit of pounds to a metric ton. Now using these production rates and given prices for each component, students will calculate what the gross annual economic potential would be of the plant, which is the profit from selling the products minus the costs of raw materials. This is shown in Equation 5.

$$\textit{Economic Potential} = \textit{Product Annual Production Rates} * \textit{Selling Prices} - \textit{Annual Soybean Feed Rate} * \textit{Cost of Raw Soybeans} \quad (5)$$

This is a very basic introduction to engineering economics in that it doesn't include labor, machine, or capital costs. Similarly, using given data for the trash that is harvested with the soybeans, students must find how many railcars of trash must be shipped per year given that a single railcar can carry 32,000 gallons. They can easily find the mass flow rate of the trash, then they must use the bulk density of trash to find what the total volume of this trash would be over a one year period. This question helps to address objective **B** for Chapter 5.

Another question presented in this section draws on a rather complicated concept that is introduced in the senior year fluid dynamics class. It requires the use of a form of the Navier-Stokes equation to find the terminal velocity of a particle based on its size, density, and drag coefficient within a particular fluid. The necessary equation, found in *Unit Operations of Chemical Engineering*, is presented as follows:

$$u_t = \sqrt{\frac{2g(\rho_p - \rho_{air})m}{A_p \rho_p C_D \rho_{air}}} \quad (6)$$

Although the question itself should not be difficult within this context, it draws on some ideas from fluid dynamics that are complicated but very important. The utilization of an equation that is not found in their text also introduces the students to the concept that they will have to use outside resources, something that is new to many of them at this stage in their education. The terminal velocity equation must be used to solve for the range of velocities of air needed to remove the hulls without also removing the beans. Data is given that will allow students to solve this based on the volumes and densities of the hulls and soybeans. Further questions regarding the air will be asked in the next portion of the assignment.

Finally, the second section of questions will require students to complete all the material balances in the system up to the first reactor section. This assignment will be finished in the second half of the semester, so students should be able to complete all these calculations with relative ease based on the concepts that have already been taught in class. In addition to these flow rates, they will be able to complete the calculations for two of the three products—protein powder and soybean oil—so they will be able to determine the purity of the protein powder product. This purity is important because it again relates to the economic concepts in that you can see the profit that can be made even with an impure product, as long as it meets regulatory requirements.

The third segment of questions that will be asked of the students mostly involves solving for parameters of the reactor sections within the process. Reactions and the balances involving them are a big part of Chapter 4, and the concepts expected for this portion are a part of objective **A**. For the first section of reactors, fermentation and reaction times are provided, and they must be used to solve for the rate constants of both fermentation and reaction. For the second reactor section, the rate constants are instead provided, and now they must solve for the residence time of fermentation and reaction. The fermentation portion operates under the equation $C=C_0e^{kt}$, while the rate equation for the reaction itself is C_0=kt, as it is a zero order reaction. Once each of these values is found for both reactor sections, students must then determine how many reactors are needed within each section to keep the process continuous. The key of this question is that the main limiting parameter of the reactors is the amount of time that it takes to fill each reactor. Therefore, the number of reactors is solved by dividing the total time needed for each reactor by the amount of time needed to fill the reactor.

Returning to the velocity of air through the aspirator, students will have to use the median velocity value to calculate a standard flow rate, which is a useful way to relate systems that don't operate under the same parameters. To do this, first find the volumetric flow rate of the process at its operating parameters by finding the reduced temperature and pressure then using compressibility charts to determine the compressibility factor for the fluid. The reduced temperature and pressure are found using the critical temperature and pressure for the fluid. Given that the fluid in question is air, there is tabulated data online for these values. However, students may be required to solve for these values themselves using all components of air and Kay's rule, which addresses objective **F** in Appendix 2. Now using the equation $P\dot{V}=z\dot{n}RT$, where z is the compressibility factor, solve for the volumetric flow rate, $\dot{V}$, at operating conditions. Although the equation above is a form of the ideal gas equation, and the air stream is not considered to be at ideal conditions, it is still valid because of the inclusion of the compressibility factor. With this volumetric flow rate and the molar flow rate, find the specific volume of the system, as it and the molar flow rate will remain constant no matter the temperature and pressure of the system. Now ratios of operating to standard temperature and pressure can be used to find the standard volumetric flow rate, a part of objective **D** for Chapter 5, which for this question is standard cubic feet per minute in this case, or SCFM.

Now using the values they have used to solve the reactor sections, students will be able to solve the remainder of the system. Past the reactor sections, they will be able to convert back to mass and use mass balances for the final product. Parts of this section may prove to be difficult because of the use of a wash stream that will be solved similarly to a recycle, which goes back to objective **A** for Chapter 4 to further test the ability to perform all aspects of mass balances. Once students have gotten to the succinic acid section, they should have a relative mastery of the content from the material balances class.

VII. Conclusion

The goal of this case study is to introduce the sophomore chemical engineers to the varied conceptual knowledge that will be expected of them as they continue through their career. The material balances class is vastly different from any other class students will have taken. It will require them to get accustomed to thinking like an engineer for likely the first time in their career. The first few weeks of learning material may be very difficult because each student will have to change their standard way of thinking and solving problems. Realistically, a sizeable fraction of people that go into the material balances class will not come out of it for one reason or another. The case study that has been presented and explained above may seem harsh at first, but these concepts are crucial for the engineers that Ole Miss is sending out into industry with only four years of education. It is for that very reason that I was happy to undertake this task so that the chemical engineers that come after me may feel as prepared and excited for industry as I am in my senior year.

VIII. Appendices

Appendix 1: Learning Objectives for Chapter 4

A. Briefly and clearly explain in your own words the meaning of the following terms: (a) batch, semi-batch, continuous, transient, and steady-state processes: (b) recycle, (c) purge, (d) degrees of freedom; (e) fraction conversion of a limiting reactant; (f) percentage excess of a reactant; (g) yield and selectivity; (h) dry-basis composition of a mixture containing water; and (i) theoretical air in a combustion reaction.

B. Given a process description, (a) draw and fully label a flowchart; (b) choose a convenient basis of calculation; (c) for a multiple-unit process, identify the subsystems for which balances might be written; (d) perform the degree of freedom analysis for the overall system and each possible subsystem; (e) write in order the equations you would use to calculate specified process variables; and (f) perform the calculations. You should be able to do these computations for single-unit and multiple-unit processes and for processes involving recycle, bypass, or purge streams. If the system involves reactions, you should be able to use molecular species balances, atomic species balances, or extents of reaction for both the degree-of-freedom analysis and the process calculations.

C. Given a combustion reactor and information about the fuel composition, calculate the feed rate of air from a given percent excess or vice versa. Given additional information about the conversion of the fuel and the absence or presence of CO in the product gas, calculate the flow rate and composition of the product gas.

Appendix 2: Learning Objectives for Chapter 5

A. Explain in your own words and without the use of jargon (a) the three ways of obtaining values of physical properties; (b) why some fluids are referred to as incompressible; (c) the "liquid volume additivity assumption" and the species for which it is most likely to be valid; (d) the term "equation of state"; (e) what it means to assume ideal gas behavior; (f) what it means to say that the specific volume of an ideal gas at standard temperature and pressure is 22.4 L/mol; (g) the meaning of partial pressure; (h) why volume fraction and mole fraction for ideal gases are identical; (i) what the compressibility factor, z, represents, and what its value indicates about the validity of the ideal gas equation of state; (j) why certain equations of state are referred to as cubic; and (k) the physical meaning of critical temperature and pressure (explain them in terms of what happens when a vapor either below or above its critical temperature is compressed).

B. For a mixture of liquids with known composition, determine V (or $\dot{V}$) from a known m ($\dot{m}$) or vice versa using (a) tabulated density data for the mixture and (b) pure-component densities and an assumption of volume additivity. Derive the density estimation formula for the second case.

C. Given any three of the quantities P, V (or $\dot{V}$), n (or $\dot{n}$), and T for an ideal gas, (a) calculate the fourth one either directly from the ideal gas equation of state or by conversion from standard conditions; (b) calculate the density of the gas; and (c) test the assumption of ideality either by using a rule of thumb about the specific volume or by estimating a compressibility factor and seeing how much it differs from 1.

D. Explain the meaning of "37.5 SCFH" (37.5 standard cubic feet per hour) and what it means to say that the flow rate of a gas stream at 120 F and 2.8 atm is 37.5 SCFH. (Why doesn't this statement specify the impossible condition that the gas is at two sets of temperatures and pressures simultaneously?) Calculate the true volumetric flow rate of that gas.

E. Given the component partial pressures of an ideal gas mixture and the total gas pressure, determine the mixture composition expressed in either mole fractions (or mole percents), volume fractions (or % v/v), or mass fractions (or % w/w).

F. Carry out *PVT* calculations for a gas using (a) the truncated virial equation of state, (b) the van der Waals equation of state, (c) the SRK equation of state, and (d) the compressibility factor equation of state with either tabulated compressibility factors or a generalized compressibility chart for a single species and Kay's rule for a non-ideal mixture of gases.

G. Given a description of a process system in which a volumetric flow rate is either specified or requested for any process stream, (a) carry out the degree-of-freedom analysis, including density estimates for liquid and solid streams and equations of state for gas streams; (b) write the system equations and outline the procedure you would use to solve for all requested quantities; (c) carry out the calculations; (d) list all your assumptions (e.g., volume additivity for liquids or ideal gas behavior) and state whether or not they are reasonable for the given process conditions.

Appendix 3: Learning Objectives for Chapter 6

A. Explain in your own words the terms *separation process, distillation, absorption, scrubbing, liquid extraction, crystallization, adsorption*, and *leaching*. (What are they and how do they work?)

B. Be able to sketch a phase diagram (*P* versus *T*) for a single species and label the regions (solid, liquid, vapor, gas). Explain the difference between a vapor and a gas. Use the phase diagram to define (a) the vapor pressure at a specified temperature, (b) the boiling point at a specified pressure, (c) the normal boiling point, (d) the melting point at a specified pressure, (e) the sublimation point at a specified pressure, (f) the triple point, and (h) the critical temperature and pressure. Explain how the melting and boiling point temperatures of water vary with pressure and how *P* and *T* vary (increase, decrease, or remain constant) as a specified path on the diagram is followed.

C. Estimate the vapor pressure of a pure substance at a specified temperature or the boiling point at a specified pressure using (a) the Antoine equation, (b) the Cox chart, (c) the Clausius–Clapeyron equation and known vapor pressures at two specified temperatures, or (d) Table B.3 for water (a table giving the vapor pressure of water at varying temperature and pressure).

D. Distinguish between intensive and extensive variables, giving examples of each. Use the Gibbs phase rule to determine the number of degrees of freedom for a multicomponent multiphase system at equilibrium, and state the meaning of the value you calculate in terms of the system's intensive variables. Specify a feasible set of intensive variables that will enable the remaining intensive variables to be calculated.

E. In the context of a system containing a single condensable species and noncondensable gases, explain in your own words the terms *saturated vapor*, *superheated vapor, dew point, degrees of superheat,* and *relative saturation*.

F. Given an equilibrated gas–liquid system containing only a single condensable component A, a correlation for $p^*_{\mathrm{A}}(T)$, and any two of the variables y_A (mole fraction of

A in the gas phase), temperature, and total pressure, calculate the third variable using Raoult's law.

G. Given a mixture of a single condensable vapor, A, and one or more noncondensable gases, a correlation for p^*_A (T), and any two of the variables y_A (mole fraction of A), temperature, and total pressure, dew point, degrees of superheat, and relative, molal, absolute, and percentage saturation (or humidity if A is water and the noncondensable gas is air), use Raoult's law for a single condensable species to calculate the remaining variables.

H. For a process system that involves a single condensable component, a vapor-liquid phase change, and specified or requested values of feed or product stream properties (temperature, pressure, dew point, relative saturation or humidity, degrees of superheat, etc.), draw and label the flowchart, carry out the degree-of-freedom analysis, and perform the required calculations.

I. Explain the meaning of the term *ideal solution behavior* applied to a liquid mixture of volatile species. Write and clearly explain the formulas for Raoult's law and Henry's law, state the conditions for which each relationship is most likely to be accurate, and apply the appropriate one to determine any of the variables $T, P, x_A,$ *or* y_A (temperature, pressure, and mole fractions of A in the liquid and gas phases) from given values of the other three.

J. Explain in your own words the terms *bubble point, boiling point,* and *dew point* of a mixture of condensable species, and the difference between *vaporization* and *boiling.* Use Raoult's law to determine (a) the bubble-point temperature (or pressure) of a liquid mixture of known composition at a specified pressure (or temperature) and the composition of the first bubble that forms; (b) the dew-point temperature (or pressure) of a vapor mixture of known composition of the first liquid drop that forms; (c) whether a mixture of known amount (moles) and composition (component mole fractions) at a a given temperature and pressure is a liquid, a gas, or a gas-liquid mixture and, if the latter, the amounts and compositions of each phase; and (d) the boiling point temperature of liquid mixture of known composition at a specified total pressure.

K. Use a *Txy* or *Pxy* diagram to determine bubble- and dew-point temperatures and pressures, compositions and relative amounts of each phase in a two-phase mixture, and the effects of varying temperature and pressure on bubble points, dew points, and phase amounts and compositions. Outline how the diagrams are constructed for mixtures of components that obey Raoult's law.

L. For a process system that involves liquid and gas streams in equilibrium and vapor-liquid equilibrium relations for all distributed components, draw and label the flowchart, carry out the degree-of-freedom analysis, and perform the required calculations.

M. Explain in your own words the terms *solubility* of a solid in a liquid, *saturated solution*, and *hydrated salt.* Given solubility data, determine the saturation temperature of a feed solution of given composition and the quantity of solid crystals that form if the solution is cooled to a specified temperature below the saturation point.

N. Given a liquid solution of a nonvolatile solute, estimate the solvent vapor-pressure lowering, the boiling-point elevation, and the freezing-point depression, and list the assumptions required for your estimate to be accurate.

O. Explain the term *distribution coefficient* (or *partition ratio*) for a solute distributed between two nearly immiscible liquids. Given feed-stream flow rates and compositions for a liquid extraction process and either solute distribution coefficient data or a triangular phase diagram, calculate the product stream flow rates and compositions.

P. Explain the term *adsorption isotherm.* Given adsorption equilibrium data or an expression for an adsorption isotherm, calculate the maximum quantity of adsorbate that can be removed from a gas by a specified quantity of adsorbent, or conversely, the minimum quantity of adsorbent needed to remove a specified quantity of adsorbate.

Appendix 4: National Society of Professional Engineers Code of Ethics

Preamble

Engineering is an important and learned profession. As members of this profession, engineers are expected to exhibit the highest standards of honesty and integrity. Engineering has a direct and vital impact on the quality of life for all people. Accordingly, the services provided by engineers require honesty, impartiality, fairness, and equity, and must be dedicated to the protection of the public health, safety, and welfare. Engineers must perform under a standard of professional behavior that requires adherence to the highest principles of ethical conduct.

I. Fundamental Canons

Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.

6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

II. Rules of Practice

1. Engineers shall hold paramount the safety, health, and welfare of the public.
    a. If engineers' judgment is overruled under circumstances that endanger life or property, they shall notify their employer or client and such other authority as may be appropriate.
    b. Engineers shall approve only those engineering documents that are in conformity with applicable standards.
    c. Engineers shall not reveal facts, data, or information without the prior consent of the client or employer except as authorized or required by law or this Code.
    d. Engineers shall not permit the use of their name or associate in business ventures with any person or firm that they believe is engaged in fraudulent or dishonest enterprise.
    e. Engineers shall not aid or abet the unlawful practice of engineering by a person or firm.
    f. Engineers having knowledge of any alleged violation of this Code shall report thereon to appropriate professional bodies and, when relevant, also to public authorities, and cooperate with the proper authorities in furnishing such information or assistance as may be required.
2. Engineers shall perform services only in the areas of their competence.

. Engineers shall undertake assignments only when qualified by education or experience in the specific technical fields involved.

   a. Engineers shall not affix their signatures to any plans or documents dealing with subject matter in which they lack competence, nor to any plan or document not prepared under their direction and control.
   b. Engineers may accept assignments and assume responsibility for coordination of an entire project and sign and seal the engineering documents for the entire project, provided that each technical segment is signed and sealed only by the qualified engineers who prepared the segment.

3. Engineers shall issue public statements only in an objective and truthful manner.

. Engineers shall be objective and truthful in professional reports, statements, or testimony. They shall include all relevant and pertinent information in such reports, statements, or testimony, which should bear the date indicating when it was current.
   a. Engineers may express publicly technical opinions that are founded upon knowledge of the facts and competence in the subject matter.
   b. Engineers shall issue no statements, criticisms, or arguments on technical matters that are inspired or paid for by interested parties, unless they have prefaced their comments by explicitly identifying the interested parties on whose behalf they are speaking, and by revealing the existence of any interest the engineers may have in the matters.

4. Engineers shall act for each employer or client as faithful agents or trustees.

. Engineers shall disclose all known or potential conflicts of interest that could influence or appear to influence their judgment or the quality of their services.
   a. Engineers shall not accept compensation, financial or otherwise, from more than one party for services on the same project, or for services pertaining to the same

project, unless the circumstances are fully disclosed and agreed to by all interested parties.

  b. Engineers shall not solicit or accept financial or other valuable consideration, directly or indirectly, from outside agents in connection with the work for which they are responsible.
  c. Engineers in public service as members, advisors, or employees of a governmental or quasi-governmental body or department shall not participate in decisions with respect to services solicited or provided by them or their organizations in private or public engineering practice.
  d. Engineers shall not solicit or accept a contract from a governmental body on which a principal or officer of their organization serves as a member.

5. Engineers shall avoid deceptive acts.

. Engineers shall not falsify their qualifications or permit misrepresentation of their or their associates' qualifications. They shall not misrepresent or exaggerate their responsibility in or for the subject matter of prior assignments. Brochures or other presentations incident to the solicitation of employment shall not misrepresent pertinent facts concerning employers, employees, associates, joint venturers, or past accomplishments.

  a. Engineers shall not offer, give, solicit, or receive, either directly or indirectly, any contribution to influence the award of a contract by public authority, or which may be reasonably construed by the public as having the effect or intent of influencing the awarding of a contract. They shall not offer any gift or other valuable consideration in order to secure work. They shall not pay a commission, percentage, or brokerage fee in order to secure work, except to a bona fide employee or bona fide established commercial or marketing agencies retained by them.

III. Professional Obligations

1. Engineers shall be guided in all their relations by the highest standards of honesty and integrity.

a. Engineers shall acknowledge their errors and shall not distort or alter the facts.

   b. Engineers shall advise their clients or employers when they believe a project will not be successful.

   c. Engineers shall not accept outside employment to the detriment of their regular work or interest. Before accepting any outside engineering employment, they will notify their employers.

   d. Engineers shall not attempt to attract an engineer from another employer by false or misleading pretenses.

   e. Engineers shall not promote their own interest at the expense of the dignity and integrity of the profession.

2. Engineers shall at all times strive to serve the public interest.

. Engineers are encouraged to participate in civic affairs; career guidance for youths; and work for the advancement of the safety, health, and well-being of their community.

   a. Engineers shall not complete, sign, or seal plans and/or specifications that are not in conformity with applicable engineering standards. If the client or employer insists on such unprofessional conduct, they shall notify the proper authorities and withdraw from further service on the project.

   b. Engineers are encouraged to extend public knowledge and appreciation of engineering and its achievements.
   c. Engineers are encouraged to adhere to the principles of sustainable development[1] in order to protect the environment for future generations.

3. Engineers shall avoid all conduct or practice that deceives the public.

. Engineers shall avoid the use of statements containing a material misrepresentation of fact or omitting a material fact.

   a. Consistent with the foregoing, engineers may advertise for recruitment of personnel.
   b. Consistent with the foregoing, engineers may prepare articles for the lay or technical press, but such articles shall not imply credit to the author for work performed by others.

4. Engineers shall not disclose, without consent, confidential information concerning the business affairs or technical processes of any present or former client or employer, or public body on which they serve.

. Engineers shall not, without the consent of all interested parties, promote or arrange for new employment or practice in connection with a specific project for which the engineer has gained particular and specialized knowledge.

   a. Engineers shall not, without the consent of all interested parties, participate in or represent an adversary interest in connection with a specific project or proceeding in which the engineer has gained particular specialized knowledge on behalf of a former client or employer.

5. Engineers shall not be influenced in their professional duties by conflicting interests.

. Engineers shall not accept financial or other considerations, including free engineering designs, from material or equipment suppliers for specifying their product.

    a. Engineers shall not accept commissions or allowances, directly or indirectly, from contractors or other parties dealing with clients or employers of the engineer in connection with work for which the engineer is responsible.

6. Engineers shall not attempt to obtain employment or advancement or professional engagements by untruthfully criticizing other engineers, or by other improper or questionable methods.

. Engineers shall not request, propose, or accept a commission on a contingent basis under circumstances in which their judgment may be compromised.

    a. Engineers in salaried positions shall accept part-time engineering work only to the extent consistent with policies of the employer and in accordance with ethical considerations.
    b. Engineers shall not, without consent, use equipment, supplies, laboratory, or office facilities of an employer to carry on outside private practice.

7. Engineers shall not attempt to injure, maliciously or falsely, directly or indirectly, the professional reputation, prospects, practice, or employment of other engineers. Engineers who believe others are guilty of unethical or illegal practice shall present such information to the proper authority for action.

. Engineers in private practice shall not review the work of another engineer for the same client, except with the knowledge of such engineer, or unless the connection of such engineer with the work has been terminated.

   a. Engineers in governmental, industrial, or educational employ are entitled to review and evaluate the work of other engineers when so required by their employment duties.
   b. Engineers in sales or industrial employ are entitled to make engineering comparisons of represented products with products of other suppliers.

8. Engineers shall accept personal responsibility for their professional activities, provided, however, that engineers may seek indemnification for services arising out of their practice for other than gross negligence, where the engineer's interests cannot otherwise be protected.

. Engineers shall conform with state registration laws in the practice of engineering.

   a. Engineers shall not use association with a nonengineer, a corporation, or partnership as a "cloak" for unethical acts.

9. Engineers shall give credit for engineering work to those to whom credit is due, and will recognize the proprietary interests of others.

. Engineers shall, whenever possible, name the person or persons who may be individually responsible for designs, inventions, writings, or other accomplishments.

   a. Engineers using designs supplied by a client recognize that the designs remain the property of the client and may not be duplicated by the engineer for others without express permission.

b. Engineers, before undertaking work for others in connection with which the engineer may make improvements, plans, designs, inventions, or other records that may justify copyrights or patents, should enter into a positive agreement regarding ownership.

c. Engineers' designs, data, records, and notes referring exclusively to an employer's work are the employer's property. The employer should indemnify the engineer for use of the information for any purpose other than the original purpose.

d. Engineers shall continue their professional development throughout their careers and should keep current in their specialty fields by engaging in professional practice, participating in continuing education courses, reading in the technical literature, and attending professional meetings and seminars.

Footnote 1 "Sustainable development" is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development.

As Revised July 2007

By order of the United States District Court for the District of Columbia, former Section 11(c) of the NSPE Code of Ethics prohibiting competitive bidding, and all policy statements, opinions, rulings or other guidelines interpreting its scope, have been rescinded as unlawfully interfering with the legal right of engineers, protected under the antitrust laws, to provide price information to prospective clients; accordingly, nothing contained in the NSPE Code of Ethics, policy statements, opinions, rulings or other guidelines prohibits the submission of price quotations or competitive bids for engineering services at any time or in any amount.

Statement by NSPE Executive Committee

In order to correct misunderstandings which have been indicated in some instances since the issuance of the Supreme Court decision and the entry of the Final Judgment, it is noted that in its decision of April 25, 1978, the Supreme Court of the United States declared: "The Sherman Act does not require competitive bidding."

It is further noted that as made clear in the Supreme Court decision:

1. Engineers and firms may individually refuse to bid for engineering services.
2. Clients are not required to seek bids for engineering services.
3. Federal, state, and local laws governing procedures to procure engineering services are not affected, and remain in full force and effect.
4. State societies and local chapters are free to actively and aggressively seek legislation for professional selection and negotiation procedures by public agencies.
5. State registration board rules of professional conduct, including rules prohibiting competitive bidding for engineering services, are not affected and remain in full force and effect. State registration boards with authority to adopt rules of professional conduct may adopt rules governing procedures to obtain engineering services.
6. As noted by the Supreme Court, "nothing in the judgment prevents NSPE and its members from attempting to influence governmental action . . ."

NOTE: In regard to the question of application of the Code to corporations vis-à-vis real persons, business form or type should not negate nor influence conformance of individuals to the Code. The Code deals with professional services, which services must be performed by real persons. Real persons in turn establish and implement policies within business structures. The Code is clearly written to apply to the Engineer, and it is incumbent on members of NSPE to endeavor to live up to its provisions. This applies to all pertinent sections of the Code.

Appendix 5: Assignment Given to Students

Soybeans have emerged as an incredibly important crop to the agriculture industry in the past century. They weren't commercially grown until the 1920's, but they have quickly grown to become one of the larger agricultural products, with the U.S. being the largest producer. Soybeans can be processed to create high quality vegetable oil, which is good for cooking purposes because of its relatively high smoke point, and protein powder, an increasingly popular product in the food and nutrition industries. The carbohydrates within the beans can also be broken down to form succinic acid, which is used widely, particularly in the food and beverage industry as an acid regulator. Today, soybean processing alone accounts for about $15 billion annually in farming. In that year, close to 24 million bushels of soybeans are produced, each bushel being 60 lbs.

There are three main components in soybeans that are important for our process. They mostly contain oil, protein, and carbohydrates, each of which is separated and utilized as a product after processing. First, the oil is pressed out of the beans. After more processing, protein powder is produced. Lastly, the remaining carbohydrates are reacted to create succinic acid as a third product. The total composition of the soybeans is presented below in Table 1.

To begin the process, raw soybeans are harvested from the field and are sent through a cleaning process where dirt and contaminants are removed. Dirt is harvested with the soybeans at 5 lb/100 lb soybeans, and 5 lb of trash are collected per 1,000 lb soybeans. The trash has a bulk density of 0.38 g/cm^3. The cleansing water in this process is fed at 1 qt water/1 lb total feed. They then go into a dryer, where lps is coming in at 160 C and is being expelled as bfw. The water within the soybeans is reduced from 14% to 9.5wt%, and this water is removed in a separate waste water stream. To continue purifying the soybeans, they are sent through an aspirator where hot air is blown over the beans to remove all of their hulls.

Once the process is relatively free of contaminants, the soybeans are put into an extruder where the first product, oil, is pressed out as its own pure stream. After pressing, the stream of beans still contains 2.5 wt% of oil. Next, the soybeans are sent into a dual extractor, meaning that the stream is split and each half is processed in a separate extractor. In this step, 10% excess of water flows into each extractor and the soluble carbohydrates go into solution. The temperature of the combined streams is 50°C. The bulk solubility of the carbohydrates at varying temperatures is given in Table 2. The process stream is then sent through a centrifuge, where the protein slurry and the carbohydrate solution are separated. 10 wt% of the protein slurry that comes out of the centrifuge is the carbohydrate solution, so the protein slurry is rinsed one more time with wash water to replace the solution that has remained in the slurry. The wash water is added at a flowrate that is double that of the solution in the slurry, and half the water goes through with the solution. Finally, the protein powder is dried with superheated steam to produce the final protein powder product.

Meanwhile, the liquid that was drawn out in the centrifuge is sent through a heat exchanger, where it is cooled to 25 °C, the ideal temperature for reaction. The polysaccharides in solution are fed into a batch reactor section, where they are all broken down into monosaccharides with Bacteria-A acting as a catalyst. Assume complete conversion. Bac-A is fed at 100 cells/L then fermented until it has grown to 100,000 cells/L. Bac-A has a mass of 0.2 kg/million cells. The fermentation process takes 2 hours, then the reaction itself takes 4 hours. Once the reaction is complete, each reactor must be emptied and rinsed, which adds an additional 30 minutes to the process. The effluent monosaccharide solution containing the remaining oil and bacteria is rinsed with wash water that is double the volume of the process stream, removing the oil and bacteria as a waste cake.

The pure monosaccharide solution is then fed into another reactor section where Bacteria-B acts as the catalyst, this time fermenting from 500 cells/L to 1,000,000 cells/L, and again with complete conversion. The bacteria has a mass of 0.08 kg/million cells. The reaction that occurs within the second reactor section is shown below:

$$C_6H_{12}O_6 \rightarrow C_4H_6O_4 + 2H_2O + C_2H_2$$

The effluent from the second reactor is filtered, and the cake of Bac-B is removed, with 5% of its weight being solution from the process stream. Now with just succinic acid in solution, the neutral stream is fed into a precipitator, where 18 M sulfuric acid is added to lower the pH of the solution to 2. Above a pH of 2.1, succinic acid solubility follows the equation:

$$\ln(sol) = -1.3516 + 0.0185T(K)$$

Below a pH of 2.1, the solubility can be found with the equation:

$$\ln(\text{sol}) = -6.4511 + 0.0203T(K)$$

Assume the combined stream is at a temperature of 100°F.

The now solid (crystalline) succinic acid is fed through a filter then a rinse tank. In the filter, half of the succinic acid solution is lost, and all the sulfuric acid is removed. The rinse tank adds wash water at a volumetric flow rate three times that of the solution flowing into it, and the resulting wastewater is fed back through the previous filter to aid in filtration. Half of the solution is lost in the filter, and half the remaining solution is lost in the rinse tank. All of the sulfuric acid leaves in the filter. It is dried, again with superheated steam, to remove the remaining water, leaving the final solid succinic acid product.

Table 1: Soybean components

Component	Weight Percent
Hull	8
Water	14
Protein	31.2
Oil	15.6
Carbs	27.3
Ash	3.9

Table 2: Carbohydrate solubility

Temperature (°C)	Solubility (g/L)
25	800
100	1350

Table 3: Carbohydrate composition

Polysaccharide	**Weight Percent**
Sucrose	30
Galactose	18
Raffinose	3
Stachyose	15
Insolubles	34

Table 4: Pricing

Item	**Cost**
Soybeans	\$9.50/bushel
Succinic Acid	\$4.50/kg
Protein Powder	\$21/kg
Soybean Oil	\$2.50/kg

Table 5: Soybean Data

	Soybean	**Hull**
Diameter	6 mm	1 cm
Height	--	3 cm
Wall Thickness	--	0.1 mm
Density	740 kg/m^3	400 kg/m^3
Drag Coefficient	1	1.8

Assignment #1

Turn in a memo/short report to Dr. O'Haver containing:

1. Names of the team members.

2. A team charter (see links below for information)

https://www.lce.com/Team-Charters-What-are-they-and-whats-their-purpose-1219.html

https://www.mindtools.com/pages/article/newTMM_95.htm

http://www.quickbase.com/blog/how-to-create-a-team-charter-for-success

3. A commitment to ethical behavior (no cheating, plagiarism, etc.)

4. A process flow diagram of the project.

All answers must be given in English units, unless otherwise specified

Assignment #2

1. Given the feed, if there were 100% recovery / production of the three products, what would be their annual production rate in metric tons?

2. Given your answers in problem 1, what is the gross potential economic value of the process? (flow rates * selling price for products – flow rate * buying price for beans) Assume the average molar mass of carbohydrates to be 300 lb/lbmol.

3. Determine how many railcars of trash will have to be sent off to composting per year, assuming one railcar can hold 32,000 gallons.

4. What range of velocities should be used in order to remove the hulls from the soybeans in the aspirator? Assume the hulls act as cylinders and the soybeans act as spheres. Relevant data is given in Table 5.

The equation for terminal velocity of a system is given as:

$$u_t = \sqrt{\frac{2g(\rho_p - \rho_{air})m}{A_p \rho_p C_D \rho_{air}}},$$

Where u_t = terminal velocity, ρ_p = particle density, A_p = cross sectional area of particle, and C_D = drag coefficient

5. What is the purity of the protein powder product?

6. Determine all streams through beginning of reactor.

Assignment #3

1. Calculate the rate constant of both the fermentation of bacteria and reaction itself in the first reactor section. In the second reaction section, find the amount of time needed to

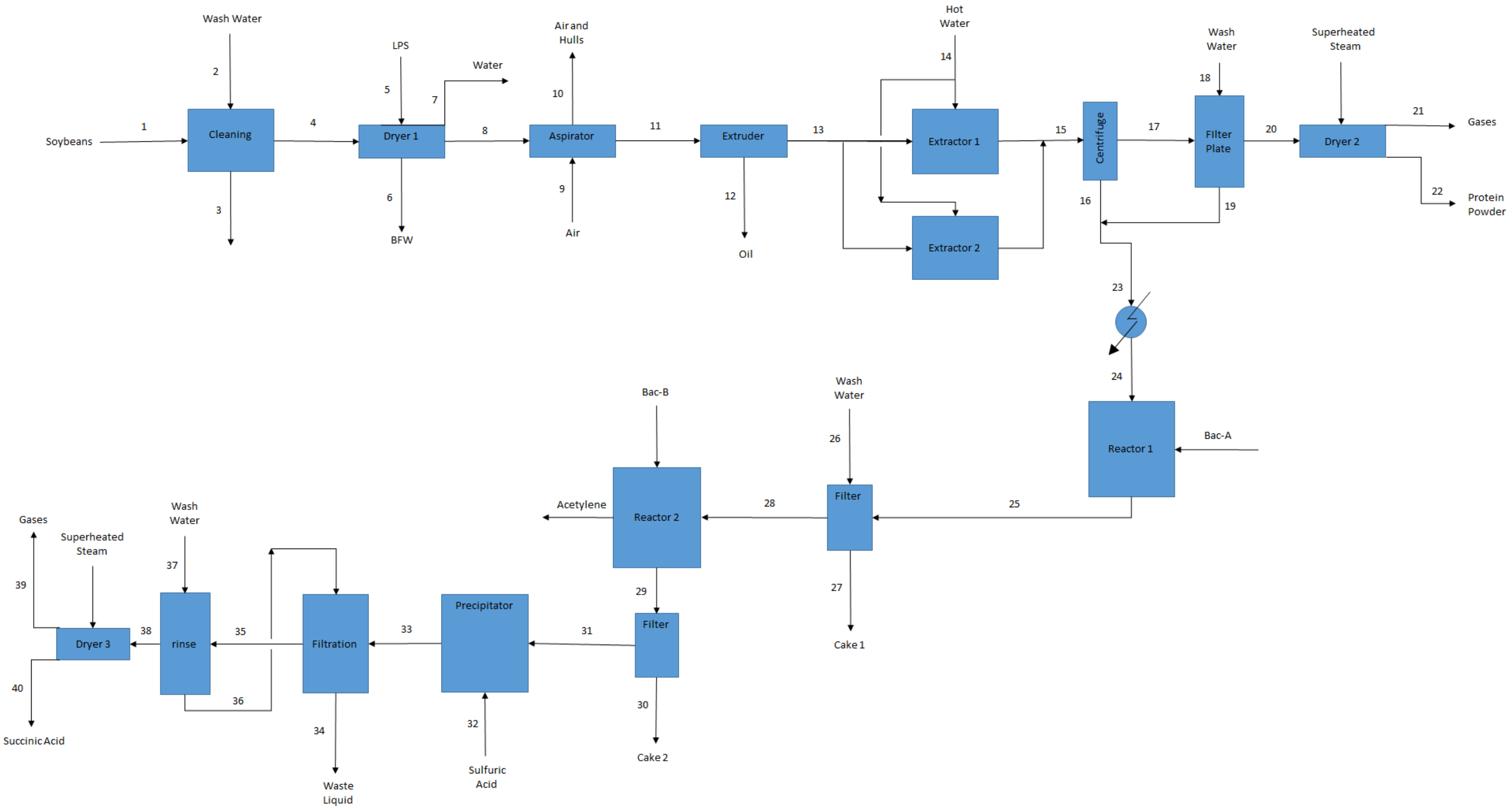
ferment and react using a rate constant of 9.7×10^{-4} 1/s for fermentation and 6.8×10^{-6} lbmol/ft^3*s for reaction. The rate equation for fermentation is given as $C = C_o e^{kt}$, and the rate equation for reaction is $C_o = kt$.

2. Determine the number of reactors needed in each reactor section to keep the process continuous. In the first section, assume each reactor has a total volume of 12,000 gallons, filled to 10,000 gallons. In the second section, assume each reactor holds 30,000 gallons and is filled to a volume of 25,000 gallons. For both sections, assume it takes 30 minutes to empty and clean each reactor.

3. Using the velocity solved for in the previous assignment, find the volumetric flow rate of compressed air at the median velocity through a 10 ft x 10 ft bed at 200 psia and 70°F. Use ALL components of air. Find the volumetric flowrate in SCFM.

4. Solve the remainder of the system.

Appendix 6: Soybean Plant Process Flow Diagram



IX. References

"5 Amazing Benefits of Soybean Oil." *Organic Facts*, Organic Information Services, 14 Mar. 2018, www.organicfacts.net/health-benefits/oils/soybean-oil.html.

"All About Soyfoods." *SoyConnection*, United Soybean Board, 8 Feb. 2017, soyconnection.com/soyfoods.

Almqvist, Henrik, et al. "Succinic Acid Production by Actinobacillus Succinogenes from Batch Fermentation of Mixed Sugars." *Journal of Industrial Microbiology & Biotechnology* , vol. 43, no. 8, Aug. 2016, pp. 1117–1130. *Springer Link*, doi:https://doi.org/10.1007/s10295-016-1787-x.

Chandran, Nyshka. "China May Be Using US Soybeans to Hit Trump's Political Base." *CNBC*, CNBC, 4 Apr. 2018, www.cnbc.com/2018/04/04/china-using-soybeans-to-hurt-president-donald-trump-jim-sutter.html.

"Code of Ethics." *National Society of Professional Engineers*, National Society of Professional Engineers, 2018, www.nspe.org/resources/ethics/code-ethics.

Coleman, Erin. "The Benefits and Drawbacks of Soy Protein Powder in Women." *Livestrong*, Leaf Group, 3 Oct. 2017, www.livestrong.com/article/467660-the-benefits-and-drawbacks-of-soy-protein-powder-in-women/.

Felder, Richard M., Ronald W. Rousseau, and Lisa G. Bullard. *Elementary Principles of Chemical Processes*. 4th ed., Wiley, 2005.

"GATT Bilateral Negotiating Material by Round." *World Trade Organization*, World Trade Organization, 2018, www.wto.org/english/docs_e/gattbilaterals_e/indexbyround_e.htm.

“Hydrogenated and Partially Hydrogenated Oils.” *Smart Balance*, Boulder Brands USA, 2017, smartbalance.com/nutrition/topics/hydrooils.

McCabe, Warren L., et al. *Unit Operations of Chemical Engineering*. 7th ed., McGraw Hill, 2004.

“Soy Processing Fact Sheet.” United Soybean Board, 2003.

“Soy Protein Powder.” *Bob's Red Mill*, Bob's Red Mill Natural Foods, 2018, www.bobsredmill.com/soy-protein-powder.html.

“Soybean Oil.” *Bulk Apothecary*, Bulk Apothecary, 8 Nov. 2016, www.bulkapothecary.com/raw-ingredients/bulk-natural-oils/soybean-oil/?msclkid=40563c5818201c57c81e66be7afa200a&utm_source=bing&utm_medium=cpc&utm_campaign=Raw Chemicals - Low Volume&utm_term=soybean

“Soybeans and Oil Crops.” *United States Department of Agriculture Economic Research Service*, United States Department of Agriculture, 19 Apr. 2018, www.ers.usda.gov/topics/crops/soybeans-oil-crops/.

“Succinic Acid.” *The Chemical Company*, The Chemical Company, 2018, thechemco.com/chemical/succinic-acid/.

Taylor, Phil. “Biosuccinic Acid Ready for Take off?” *Chemistry World*, Royal Society of Chemistry, 21 Jan. 2010, www.chemistryworld.com/news/biosuccinic-acid-ready-for-take-off/3000559.article.

“The Benefits of Soybean Oil: A Well-Balanced & Versatile Oil.” *SoyConnection*, United Soybean Board, 24 Oct. 2017, soyconnection.com/soybean-oil.

Thiesse, Kent. “Grain Prices Fall Sharply after USDA Releases Grain Supply and Demand Report.” *Corn and Soybean Digest*, Informa USA, 18 July 2016, www.cornandsoybeandigest.com/blog/grain-prices-fall-sharply-after-usda-releases-grain-supply-and-demand-report.

Vaswani, Sudeep. “Bio-Based Succinic Acid.” *SRI Consulting Review*, Dec. 2010, doi:10.3897/bdj.4.e7720.figure2f.

Wolke, Robert L. “Where There's Smoke, There's a Fryer.” *The Washington Post*, The Washington Post Company, 16 May 2007, www.washingtonpost.com/wp-dyn/content/article/2007/05/15/AR2007051500398.html.