

# **BINDER FOR OUTCOME "3"**

*"An ability to communicate effectively with a range of audiences."*

**COLLEGE OF ENGINEERING  
CHEMICAL ENGINEERING DEPARTMENT  
PRAIRIE VIEW A&M UNIVERSITY**

**BINDER CONTAINING REPRESENTATIVE  
ASSIGNMENTS FROM ALL COURSES USED TO  
ASSESS OUTCOME "3"**

**Last 4 Academic Years**

*09/14/2022 Revision*

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- 3. List of courses used to assess this outcome**
- 4. Summary Assessment Results and Continuous Improvements for outcome**
- 5. Sample Assignments and Justification of suitability for measuring the outcome in :**
  - CHEG 4101 Chemical Engineering Laboratory II**
  - CHEG 4104 Chemical Engineering Laboratory III**
  - CHEG 4248 Senior Design and Professionalism-II**



## 2. Description of Outcome "3" and its Performance Criteria

### Outcome 3:

*An ability to communicate effectively with a range of audiences*

### Sub-Outcomes and Performance Criteria

3.1: Ability to Organize, Plan, Design/Prepare and Use Appropriate Visual Aids for communication/Presentation to a range of audiences (executives, technical and non-technical).

3.2: Ability to Articulate Subject Knowledge (Technical Content)

3.3: Appearance and Ability to Provide Good Oral Delivery to a range of audiences

3.4: Ability to prepare an executive summary for the report

3.5: Ability to organize, plan and properly format a written technical report

3.6 Ability to compose original texts and properly apply the conventions of written language

3.7: Ability to provide appropriate discussion, conclusions and recommendations

## 3. List of Courses Used to Assess the Outcome

Outcome 3 is assessed in the following courses:

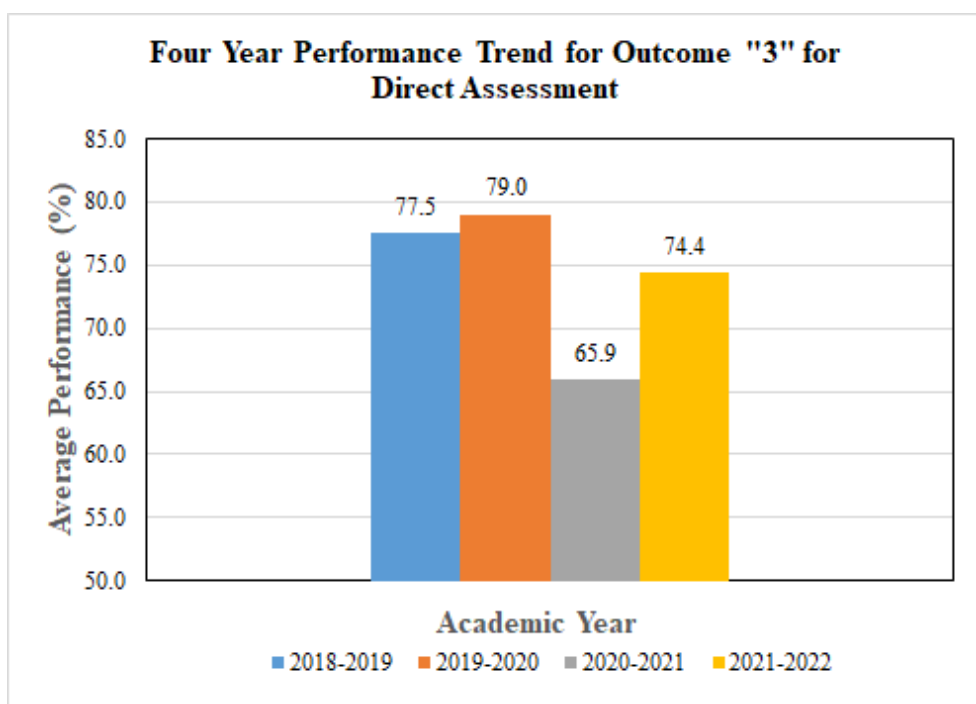
CHEG 4101 Chemical Engineering Laboratory II

CHEG 4104 Chemical Engineering Laboratory III

CHEG 4248 Senior Design and Professionalism-II

## 4. Summary Assessment Results and Continuous Improvements for Outcome "3" over the Assessment Years.

The average performance for all students in the 3 courses used to assess outcome 3 for the past four academic years are shown below



## Problems identified and recommended actions to be taken to address problems

### 1. At the course level

| Problems Identified in the Various Courses                                                                                                                                                                                                                                                                                                                                                                                                   | Recommended Actions Taken                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | Basis for Action                                                                       |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| <ol style="list-style-type: none"><li>1. In the written communications, some students showed difficulty in correct grammatical expression.</li><li>2. A more serious and pervasive issue is students having difficulty in writing logical conclusions and giving adequate discussion to the results that they generate in experimental work.</li><li>3. Students find it difficult to reference citations in their written reports</li></ol> | <ol style="list-style-type: none"><li>1. Communicate with the English department to emphasize technical writing aspects, including referencing citations, to the students.</li><li>2. Use anonymized actual reports to demonstrate what makes a good report.</li><li>3. Continue conducting a class session on rules guiding technical writing such as reference citation</li><li>4. Encourage students to discuss their draft reports and presentations with the instructor BEFORE turning them in.</li><li>5. Reintroduction in the degree plan of CHEG 3011(Chemical Engineering Laboratory I) to help enhance technical reporting skills of the students</li></ol> | Continuous improvement on the actions and efforts adopted so far to achieve this feat. |

### 2. At Department Level

(1) Faculty members in the program met periodically to review data from the Program Outcome Assessment Reports. The weak areas of outcomes performance were identified. Perceived problems were discussed in this forum. Faculty were provided with the data collected from student exit surveys for their review, as well as input from the Industrial Advisory Council (IAC). .

(2) CHEG 3011, Chemical Engineering Laboratory I, a one-credit hour course, which is already in the course inventory will be reintroduced. This course will be revamped to include elements and methods of scientific inquiry and investigation, experimental data analysis, modeling and simulation, and dissemination of scientific results, including: design of experiments, product and process design, model validation and verification, literature survey and review techniques, and effective technical reporting modes. .

#### Basis of Action:

The students' performance average for Outcome 3 in the last two academic cycles (2018-2019 and 2019-2020) were above the target average of 75%. Besides, the aggregate percentage of students (91 % and 82 %) meeting the expected average in the last two academic cycles were above the set target of 70 %. The basis for action is to continue to improve upon the achievement so far by strengthening the various strategic actions and efforts adopted to achieve this feat.

**6. Sample Assignments and Justification of suitability of assignment for measuring the outcome in :**

**CHEG 4011 Chemical Engineering Laboratory II**  
**CHEG 4031 Chemical Engineering Laboratory III**  
**CHEG 4482 Senior Design and Professionalism-II**

**OUTCOME “3” SPECIFIC ASSIGNMENTS  
USED TO ASSESS THE OUTCOME IN**

**CHEG 4031  
CHEMICAL ENGINEERING  
LABORATORY III**

**CHEMICAL ENGINEERING DEPARTMENT  
OUTCOMES SPECIFIC ASSIGNMENT COVER SHEET  
CHEMICAL ENGINEERING LABORATORY III  
SPRING 2020**

**Instructor: Dr. Jorge F. Gabitto**

**Title of Assignment**

**Final Presentation**

**Outcome Measured Using this Assignment**

**Outcome 3**

An ability to communicate effectively with a range of audiences

**Brief justification of why this assignment is suitable for this outcome**

This assignment involves an oral presentation evaluated on technical content, slide preparation, professional delivery, and design content.

# Sample Work

# Kinetics of a (Solid-Liquid) Esterification Reaction

By: Ashley Gutierrez  
Saidou Niandou Hassane  
Patricia Ujeyah  
Jaliil Zoundi

## Overview

- Problem Statement
- Theory
- Abstract
- Experimental Set-Up
- Procedures
- Expected Results
- Discussion
- Conclusion
- References





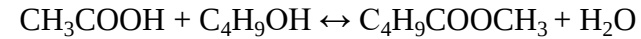
# Problem Statement

- Determine the reaction rate constants for the forward and backward reactions for esterification of acetic acid and n-butanol at different temperatures



# Theory

Reaction:



Acetic Acid + Butanol  $\leftrightarrow$  Butyl Acetate + Water

Kinetic Model:

Among all the models the simplest model is the pseudo homogeneous model given by the following equation;

$$-r_{\text{CH}_3\text{COOH}} = K_1 C_{\text{CH}_3\text{COOH}} C_{\text{C}_4\text{H}_9\text{OH}} - K_2 C_{\text{C}_4\text{H}_9\text{COOCH}_3} C_{\text{H}_2\text{O}}$$

Where K is the reaction equilibrium constant (i.e.  $k_1/k_2$ ) that can be independently calculated using the following relation:

$$\ln \frac{K}{K^0} = \frac{\Delta H_R^{0(L)}}{R} \left[ \frac{1}{T_0} - \frac{1}{T} \right]$$

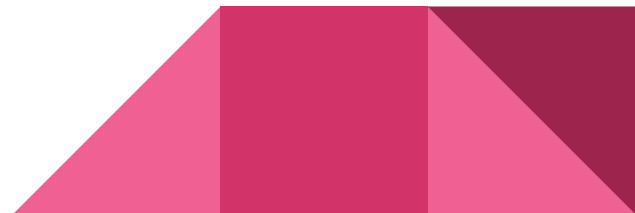
$$\text{Where: } K^0 = \exp \left[ -\frac{\Delta G_R^{0(I)}}{RT_0} \right]$$

$$\text{Data: } \Delta H_R^{0(L)} = -3.887 \frac{\text{kJ}}{\text{mol}}, \Delta G_R^{0(I)} = -8.89 \text{ kJ/mol}$$

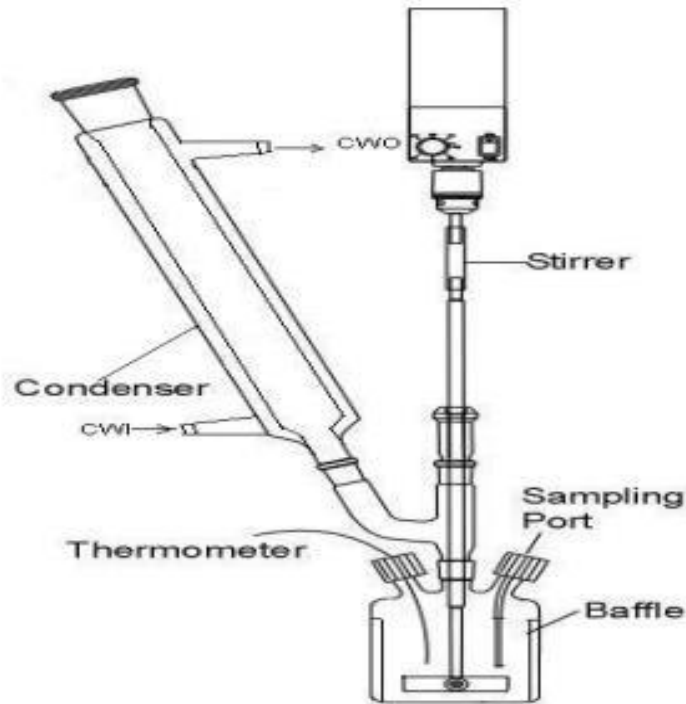


## Abstract

- The synthesis of butyl acetate is done through esterification of acetic acid with-butanol
- Esters has many wide applications, as well as a versatile solvent within the chemical industry
- Within this experiment:-
  - presence of acid catalyst
  - Catalyst- Solid heterogeneous
  - Reactions takes place on the surface of the catalyst



## EquipmentSet-Up



**Figure 1:** Experimental Set up

Equipment Used:

Thermometer,  
Condenser,  
Sampling Port,  
Stirrer, and Baffle

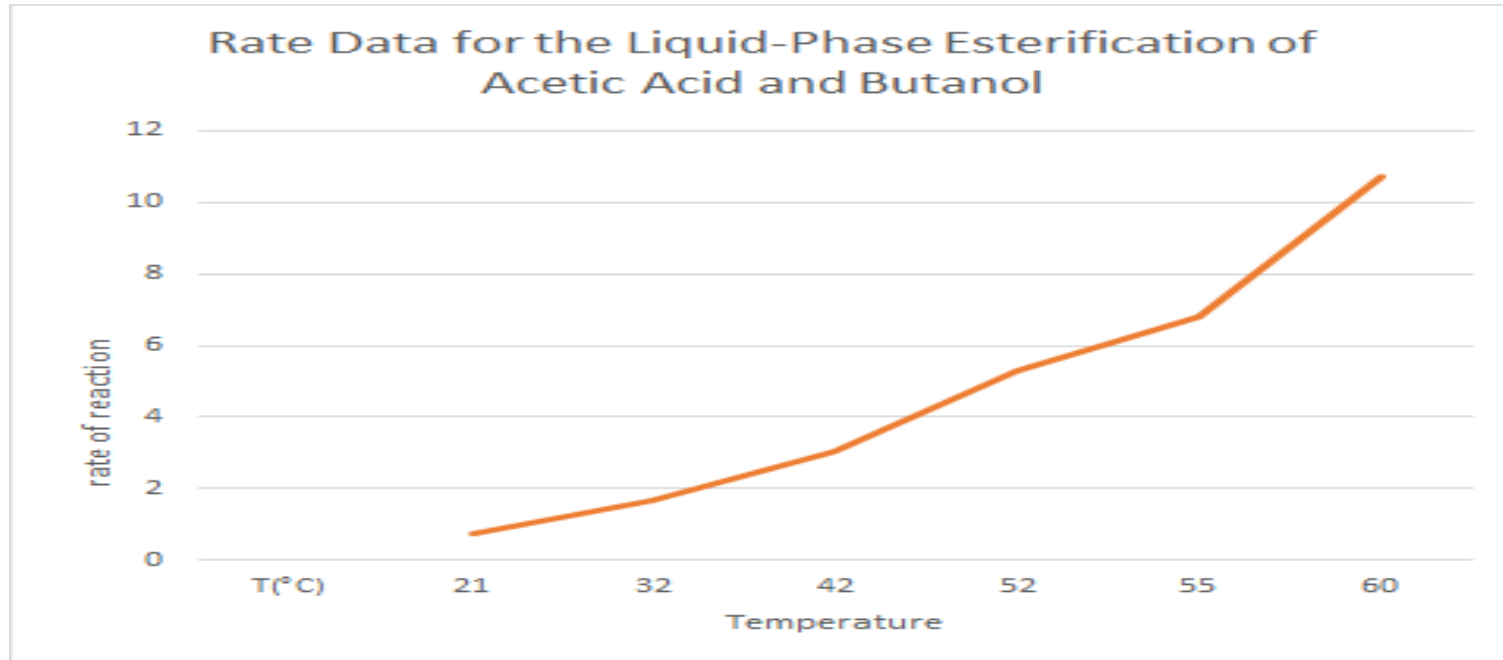
# Procedure

1. Set the temperatures of the heating chambers (at least four) at the desired levels and start heating.
  2. Take measured quantities of acetic acid and n-butanol in the two reactors.
  3. Place the reactors in the oil baths, start slow stirring and observe the reactor temperature.
  4. Once the desired temperature of the reaction mixture is attained, add the measured quantity of cation exchange resin (Amberlyst-15) in the reactor. Consider this time as the zero reaction time.
  5. Increase the speed of agitation to 1200 rpm.
  6. Remove samples from all the reactors.
  7. Keep removing the samples as per the time intervals indicated in the tables.
  8. Titrate weighed quantity of the sample against 0.5 M NaOH.
  9. Record the titration readings and calculate conversions at every time interval.
- 

## Expected Result

| Column1 ▼ | Column2 ▼                               | Column3 ▼                                      |
|-----------|-----------------------------------------|------------------------------------------------|
| T(°C)     | $r_0 * 10^3 {}^a (mol L^{-1} min^{-1})$ | $K_{auto} * 10^6 {}^b (L^2 mol^{-1} min^{-1})$ |
| 21        | 0.76                                    | 0.97                                           |
| 32        | 1.68                                    | 2.15                                           |
| 42        | 3.03                                    | 3.87                                           |
| 52        | 5.3                                     | 6.77                                           |
| 55        | 6.83                                    | 8.73                                           |
| 60        | 10.7                                    | 13.7                                           |

# Result Graph



# Discussion

- From the result we can observe an increase in the rate of reaction as the temperature increases
- This reaction is therefore temperature sensitive
- To reach a greater yield the temperature needs to be reach 60°C





# Conclusion

- Esterification Reaction of Acetic Acid with butanol was successful
- Investigations were conducted with the effect of molar ratios, temperatures, and catalyst
- A stir speed  $\geq 800$  rpm was found sufficient for eliminating external diffusion
- The conversion of the alcohol increased with increasing temperatures and initial amount of acid



# Conclusion cont.

- **Safety:**                      **Hazard: flammable materials, corrosive material**

Risk: Glassware breaking, fire ignition

Mitigation: Rigorous training and extinguisher

- **Economics:** Condenser- \$50 , Thermometer- \$10, Stirrer- \$400, Sampling Port- \$55 , Baffle- \$130

Total: \$645

- **Feasibility:** 1-2 hrs experiment, comprehensive material cost
- **Sustainability :** Maintenance is minimal and affordable

# References

- [1]. B. RabindramJermy, A. Pangurangam, "A highly efficient catalyst for the esterification of acetic acid using n- Butyl alcohol", Journal of molecular catalysis, 237(2005), 146-154.
- [2]. S. Ismail, Lirbaslar, UmurBramur, "esterification of acetic acid with ethanol catalyzed by an acidic ion exchange resin", turkJournal of Environmental science, 25(2001), 569-579



**CHEMICAL ENGINEERING DEPARTMENT  
OUTCOMES SPECIFIC ASSIGNMENT COVER SHEET  
CHEMICAL ENGINEERING LABORATORY III  
SPRING 2020**

**Instructor: Dr. Jorge F. Gabitto**

**Title of Assignment**

Typical Laboratory Report

**Outcome Measured Using this Assignment**

**Outcome 3**

An ability to communicate effectively with a range of audiences

**Brief justification of why this assignment is suitable for this outcome**

This assignment involves a written report evaluated on technical content, grammar, professional writing, and report organization.

**Prairie View A&M University**

Roy G. Perry College of Engineering



## Virtual Lab Experiment I

CHEG 4031-Lab III

Prepared By:

Vatallio Abrams II  
James Fearon  
Maya Hunter  
Alexandria Ward

Due Date: April 8th, 2020  
Submitted to: Dr. Gabitto

## **Table of Contents**

Abstract

Theory

Procedure

Results & Discussion

Conclusion

## **Abstract**

A proportional-integral-derivative-controller (PID) is widely used in industrial settings to provide feedback for instrumentation that monitors vessels present on the plant floor. This experiment explores those controls and demonstrates how signals delivered by the control loop mechanism affect reaction progression, level control, pressure valves, and bypass loops to name a few. The data populated and recorded in this report specifically relates to a level control meter.

## **Theory**

A proportional-integral-derivative controller (PID controller or three-term controller) is a control loop mechanism used in various applications that require continuous control. A PID controller continuously calculates an error value ( $e(t)$ ) as the difference between the desired setpoint (SP) and a measured process variable (PV). It then applies a correction based on proportional, integral, and derivative terms (noted as P, I, and D). The use of the PID controller does not guarantee proper control of the system or stability. The response of the controller can be described by the response to error, which is the system overshooting a setpoint and causing any oscillation in the system. The PID controller can be used in any type of control situation. This is the case because the controller only relies on the response of the process variable and nothing else.

Applicable equations:

The output variable value ( $u(t)$ ) is given by,

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d e(t)}{dt}, \quad (1)$$

Here;  $K_p$ ,  $K_i$ , and  $K_d$ , are the proportional, integral, and derivative constants, respectively. In the standard form eq. (1),  $K_i$  is replaced by  $K_p / T_i$  and  $K_d$  by  $K_p T_d$  leading to,

$$u(t) = K_p e(t) + \frac{K_p}{T_i} \int_0^t e(\tau) d\tau + K_p T_d \frac{d e(t)}{dt}. \quad (2)$$

Here,  $T_i$  and  $T_d$  physically represent the integral and derivative time, respectively.

## **Procedure**

This experiment will be based on inputting different values for P, I and D constants for a PID1 controller. The procedure which will be used is as follows:

1. Press START in the top left corner.
2. A dialogue box will ask you for a file name. The measured data will be recorded in this file.
3. Input a set of values for the P, I and D parameters of the PID1 controller.
4. Press record and set the time interval (in seconds) between data.
5. Change the setpoint to the value listed in Table 1.



6. Run the experiment for 5 minutes or until a steady-state is reached.
7. Repeat the procedure for the three times listed in Table 1 for each type of controllers, P/PI/PID.
8. After the third set press STOP and retrieve the data file.
9. Repeat the whole procedure for the other two types of controllers. After changing the controller type ALWAYS reset the set point to the original value (120 mm.)
10. Process the three data files.

# Prairie View A&M University

Roy G. Perry College of Engineering



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20. Process the three data files.

## **Results And Discussion**

Based on these results it can be determined that the level control meter does function. However, in relation to the setpoints, some tests produced results that were either overshoot or under-shoot. The PID (Proportional-Integral-Derivative) parameters are optimised for steady state control at

or near the setpoint, high and low cutback parameters are used to reduce overshoot and undershoot for large step changes in conditions of the system. They respectively set the number of degrees above and below the set point at which the controller will start to increase or reduce the output power. In the lab certain errors can result in results being off such as incorrect calibration to sensors, nonlinearity, and inversions of on or off controls or interchange of controls of the pumps. The unit physically simulates dynamic systems under the operation of the process unit and the control loops which was seen in the virtual lab. The graphs which were generated during this experiment, the best controller used would be the PID controller due to the behavior settling in with faster response time. Also, after comparing the set points of all three graphs, the PID controller was observed to be the best when it came to the instantaneous performance of the system. The PID action graphs were displayed after closing or opening of the actuators, which shows the real time value of the real time value approaching the setpoint value. The PID actuator close to prevent flow from the pump and provides constant level for the results and graphs to be obtained correctly and the solenoid or manual valve modify level in the tank. The PID actuator closes due to process control as the values get to the setpoint values. Also instead of using the PC to control the system is the use of Programmable Logic Controllers (PLC) which can do input and output configuration of the system to manipulate or check for errors which were listed above in having more accurate results and plots. These help for multiple control functions to be carried out with instantaneous response to the system.

## **Conclusion**

The effect of the Proportional, Integral Derivative settings on the behavior of a three term PID Controller (proportional-integral-derivative) used for level control was shown and control system and processes were made clear. After looking at all of the graphs which were generated during

this experiment, the best controller used would be the PID controller due to the behavior settling in a shorter time frame. Also, after comparing the set points of all three graphs, the PID controller was still the best when it came to performance. The overall conclusion for this experiment is that the PID controller would be the most useful to achieve the desired results and set point.

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## **Grading Rubric**

Group: Vatalio Abrams II, James Fearon, Maya Hunter, Alexandria Ward

| <b>Technical Content</b> | <b>Maximum</b> | <b>Grade</b> |
|--------------------------|----------------|--------------|
| Abstract/Objective       | 5              | 3            |
| Theory                   | 5              | 4            |
| Results                  | 5              | 4            |
| Conclusions              | 5              | 3            |
| <b>Total = 14/20</b>     | 20             | 14           |

|                                |    |   |
|--------------------------------|----|---|
|                                |    |   |
| <b>Writing Content</b>         |    |   |
| Organization                   | 5  | 5 |
| Language                       | 5  | 3 |
| Professional content           | 5  | 4 |
| Appearance                     | 5  | 4 |
| <b>Total = 16/20 for 30/40</b> | 20 | 6 |

**OUTCOME “3” SPECIFIC ASSIGNMENTS  
USED TO ASSESS THE OUTCOME IN**

**CHEG 4482 - SENIOR DESIGN AND  
PROFESSIONALISM II**





**CHEMICAL ENGINEERING DEPARTMENT  
OUTCOMES SPECIFIC ASSIGNMENT COVER SHEET  
SENIOR DESIGN AND PROFESSIONALISM II  
SPRING 2020**

**Instructor: Dr. Lealon L. Martin**

**Title of Assignment**

FINAL REPORT

**Outcome Measured Using this Assignment**

**Outcome 3**

**An ability to communicate effectively with a range of audiences  
(Written Technical Communication)**

**Check the complex engineering problem characteristics related to this assignment**

| Assignment problem                                               |                                                                   |
|------------------------------------------------------------------|-------------------------------------------------------------------|
| X                                                                | involves wide-ranging or conflicting technical issues,            |
| X                                                                | has no obvious solution                                           |
| X                                                                | Addresses problems not encompassed by current standards and codes |
| X                                                                | involves diverse groups of stakeholders                           |
| X                                                                | includes many component parts or sub-problems                     |
| X                                                                | involves multiple disciplines                                     |
| X                                                                | has significant consequences in a range of contexts               |
| Assignment problem involves the application of the principles of |                                                                   |
| X                                                                | engineering                                                       |
|                                                                  | science                                                           |
| X                                                                | mathematics                                                       |

**Brief justification of why this assignment is suitable for this outcome**

This final report tests competency in written communication and students' ability to logically arrange information, use correct grammar, use appropriate format, use discipline specific conventions including citations, and use acceptable graphical **Sample of graded student's solution** conventions.

**Problem Statement & Grading Scheme Sample  
Graded Student Work**

## End of Semester Project Report Format

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### **1. Letter of Transmittal**

The letter of transmittal captures the main points in in the EXECUTIVE SUMMARY.

- (i) It clearly spells out why the report has been prepared.
- (ii) Essential results, conclusions and recommendations are presented  
See your College of Engineering Senior Design Manual for an example.

### **2. The EXECUTIVE SUMMARY**

Your Executive Summary is a carefully distilled form of your complete design report and should have the following components:

- (a) It should clearly state the need for the design and its objectives (b) It should clearly summarize what was done and main findings ( process and production capacity, plant location and plant design and capital cost estimates, the capital investment , return on investment including, discounted cash flow internal rate of return, payback period etc)
- (c) How the final results were obtained
- (d) Clearly presented conclusions and recommendations.

## **Design Constraints and Design Basis**

### **External constraints:**

- 1. Physical laws
- 2. Standards and codes

3. Economic
4. Government and safety regulations
5. Resources

**Internal constraints:**

1. Choice of process
2. Process conditions
3. Materials and equipment
4. Time (for completion of design)
5. Personnel

**Setting the Design Basis**

1. Production rate
2. Purity specifications of the main product
3. The system of units to be used
4. The national, local, or company design codes that must be followed
5. Details of raw materials that are available
6. Information on potential sites where the plant might be located, including climate data, seismic conditions, and infrastructure availability
7. Information on the conditions, availability, and price of utility services such as fuel gas, steam, cooling water, process air, process water, and electricity that will be needed to run the process

**DEPARTMENT OF CHEMICAL ENGINEERING  
SENIOR DESIGN & PROFESSIONALISM II CHEG 4482  
COURSE ASSESSMENT GRADING & OUTCOME  
ASSESSMENT SHEET FOR SPRING 2019 SEMESTER**

---

**ABET Student Learning Outcome 3: An ability to communicate effectively with a range of audiences (Written Technical Communication)**

Assignments that test competency in written communication will include problems that test the student's ability to logically arrange information, use correct grammar, use appropriate format, use discipline specific conventions including citations, and use acceptable graphical conventions.

---

Name: \_\_\_\_\_

Title of Assignment: \_\_\_\_\_ Due Date \_\_\_\_\_

| Competency Area                                                   | Points Assigned | Points Received |
|-------------------------------------------------------------------|-----------------|-----------------|
| <b>1. Ability to prepare an executive summary for the report</b>  | <b>10</b>       |                 |
| Students are able to prepare an executive summary of 5 to 8 pages | <b>10</b>       |                 |



|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |            |  |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|--|
| <b>2. Ability to organize, plan and properly format a written technical report</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <b>80</b>  |  |
| (i) Students are able to organize report by categorizing ideas for the report into well and logically organized chapters, major sections, subsections and paragraphs blended within the larger units.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 20         |  |
| (i) Students are able to organize report by categorizing ideas for the report into well and logically organized chapters, major sections, subsections and paragraphs blended within the larger units.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 20         |  |
| (ii) Students provide Title Page, and Table of Contents, list of Figures, and List of Tables properly formatted.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 12         |  |
| (iii) Students provide figure number and title for each figure in the report, reference each figure, and completely discuss each figure in the report in accord with standards in the project manual.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 12         |  |
| (iv) Students provide table number and title for each table in the report in accord with standards in the project manual, reference each table, and completely discuss each table in the report.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 12         |  |
| (v) Students properly cite references in the report and provide well formatted reference list at the end.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 12         |  |
| (vi) Students prepare the written report in accord with standard report formatting provided in the Senior Projects Report Manual.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 12         |  |
| <b>3. Ability to compose original texts and properly apply the conventions of written language</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | <b>50</b>  |  |
| (i) Properly apply capitalization, punctuation, and penmanship, to communicate clearly.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 15         |  |
| (ii) Spell proficiently                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 10         |  |
| (iii) Apply standard grammar and usage to communicate clearly and effectively in writing including <ul style="list-style-type: none"> <li>• using complete sentences, varying the types such as compound and complex to match meanings and purposes</li> <li>• properly employing standard English usage in writing for audiences, including subject-verb agreement, pronoun referents, and parts of speech</li> <li>• properly using adjectives (comparative and superlative forms) and adverbs appropriately to make writing vivid or precise</li> <li>• properly using prepositional phrases to elaborate written ideas</li> <li>• properly using conjunctions to connect ideas meaningfully</li> </ul> | 20         |  |
| (vi) Use available technology to support aspects of creating, revising, editing, spell checking, and publishing the report.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 5          |  |
| <b>4. Ability to provide appropriate discussion, conclusions and recommendations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | <b>60</b>  |  |
| (i) Summarize the goals, objectives, and indicate whether they were met.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 10         |  |
| (ii) Summarize the results.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 30         |  |
| (iii) Summarize constraints and codes and indicate whether they were met.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 10         |  |
| (iv) Provide logical conclusions and recommendations (including strengths and weaknesses).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10         |  |
| <b>Total</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | <b>200</b> |  |

**DEPARTMENT OF CHEMICAL ENGINEERING**  
**SENIOR DESIGN & PROFESSIONALISM II CHEG 4482**  
**COURSE ASSESSMENT GRADING & OUTCOME**  
**ASSESSMENT SHEET FOR SPRING 2019 SEMESTER**

**ABET Student Learning Outcome 3: An ability to communicate effectively with a range of audiences (Written Technical Communication)**

Assignments that test competency in written communication will include problems that test the student's ability to logically arrange information, use correct grammar, use appropriate format, use discipline specific conventions including citations, and use acceptable graphical conventions.

Name: Group 2 (Bio)

Title of Assignment: Final Report Due Date: 5/6/2020

| Competency Area                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | Points Assigned | Points Received |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------|-----------------|
| <b>1. Ability to prepare an executive summary for the report</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 10              | 10              |
| Students are able to prepare an executive summary of 5 to 8 pages                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 10              | 10              |
| <b>2. Ability to organize, plan and properly format a written technical report</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 80              | 80              |
| (i) Students are able to organize report by categorizing ideas for the report into well and logically organized chapters, major sections, subsections and paragraphs blended within the larger units.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 20              | 20              |
| (i) Students are able to organize report by categorizing ideas for the report into well and logically organized chapters, major sections, subsections and paragraphs blended within the larger units.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 20              | 20              |
| (ii) Students provide Title Page, and Table of Contents, list of Figures, and List of Tables properly formatted.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 12              | 12              |
| (iii) Students provide figure number and title for each figure in the report, reference each figure, and completely discuss each figure in the report in accord with standards in the project manual.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | 12              | 12              |
| (iv) Students provide table number and title for each table in the report in accord with standards in the project manual, reference each table, and completely discuss each table in the report.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 12              | 12              |
| (v) Students properly cite references in the report and provide well formatted reference list at the end.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 12              | 12              |
| (vi) Students prepare the written report in accord with standard report formatting provided in the Senior Projects Report Manual.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 12              | 12              |
| <b>3. Ability to compose original texts and properly apply the conventions of written language</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 50              | 50              |
| (i) Properly apply capitalization, punctuation, and penmanship, to communicate clearly.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 15              | 15              |
| (ii) Spell proficiently                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 10              | 10              |
| (iii) Apply standard grammar and usage to communicate clearly and effectively in writing including <ul style="list-style-type: none"> <li>• using complete sentences, varying the types such as compound and complex to match meanings and purposes</li> <li>• properly employing standard English usage in writing for audiences, including subject-verb agreement, pronoun referents, and parts of speech</li> <li>• properly using adjectives (comparative and superlative forms) and adverbs appropriately to make writing vivid or precise</li> <li>• properly using prepositional phrases to elaborate written ideas</li> <li>• properly using conjunctions to connect ideas meaningfully</li> </ul> | 20              | 20              |
| (vi) Use available technology to support aspects of creating, revising, editing, spell checking, and publishing the report.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 5               | 5               |
| <b>4. Ability to provide appropriate discussion, conclusions and recommendations</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | 60              | 50              |
| (i) Summarize the goals, objectives, and indicate whether they were met.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | 10              | 10              |
| (ii) Summarize the results.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 30              | 25              |
| (iii) Summarize constraints and codes and indicate whether they were met.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 10              | 7               |
| (iv) Provide logical conclusions and recommendations (including strengths and weaknesses).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10              | 8               |
| <b>Total</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 200             | 190             |



“Design of a Grass-root Plant for the Production of Glucose-Fructose Syrup”

Senior Design & Professionalism II Final Report

Submitted by

Charles Kellum

Kameron Flournoy

Sabrina Noe

Temiloluwa Oluyadi

Unyime Effiong

To

Dr. Lealon Martin

Senior Design Instructor

Department of Chemical Engineering

College of Engineering

Prairie View A&M University

May 4, 2020

*Very good  
report  
overall.*

*You need  
to be  
careful  
with tens*



## LETTER OF TRANSMITTAL

May 4th, 2020

Department of Chemical Engineering  
Prairie View A&M University  
700 University Drive  
Prairie View, TX 77446

Dear Dr. Martin,

Based on our senior design problem statement, we were able to complete the design of a chemical plant that produces high fructose corn syrup (HFCS) after evaluating various design alternatives using a theoretical economic indicator. Enclosed in this report, you will find our plant design to produce approximately 705 million pounds per year of HFCS through enzymatic corn starch hydrolysis. Of this total syrup production, 52% will be syrup containing 55% fructose (364 million annually) and the remaining will be syrup containing 42% fructose (341 million annually). Enzymatic corn starch hydrolysis was the production route selected and information about design specifications of major equipment, a HAZOP analysis of the packed bed reactor for glucose isomerization, and an economic analysis of the entire plant are provided

Sincerely,

  
\_\_\_\_\_  
Sabrina Noe

  
\_\_\_\_\_  
Unyime Effiong

  
\_\_\_\_\_  
Charles Kellum

  
\_\_\_\_\_  
Kameron Flournoy

  
\_\_\_\_\_  
Temiloluwa Oluyadi



## **ACKNOWLEDGEMENTS**

We would like to acknowledge the staff of the Roy G. Perry College of Engineering-Department of Chemical Engineering at Prairie View A&M University for providing resources and advice that were essential to the completion of this senior design project. Special thanks to Dr. Lealon Martin and Dr. Michael Gyamerah for advising the bioengineering senior design groups. The assistance of the Industrial Advisory Council in judges the design presentations as well as providing helpful feedback on the project design is also highly appreciated.





## EXECUTIVE SUMMARY

The goal of this project is to design a chemical plant that produces glucose-fructose syrup that will cater to the supply and demand for this product within the food and beverage industry. This will be accomplished by making a complete design for all major equipment, conducting a plant economic analysis, creating a control scheme and performing a HAZOP analysis for one major equipment. The production of high fructose corn syrup (HFCS) involves three catalytic reactions (liquefaction, saccharification, and glucose isomerization) which are carried out within our major equipment. In the process of production, purification steps using ion exchangers, absorption columns, and a rotary filter are essential to ensure product quality specifications are met. The total plant capacity is 706 MM lbs/yr (1.5 M metric tons) with a production run time of 330 days annually. Two grades of syrup; HFCS 42 (used for food processes and baked goods) and HFCS 55 (used for carbonated drinks and juices) will be produced at an annual rate of 341 MM lbs/yr and 365 MM lbs/yr respectively. The plant is located in Asbury, Iowa and the plant life is 20 years. HFCS 42 and HFCS 55 are sold at 25.5 ¢/lb and 32.75 ¢/lb respectively. Based on economic analysis, the total module cost of all the equipment is about \$73 million and the cost of manufacturing without depreciation is about \$113 million. The total capital investment is about \$88 million and net annual profit is about \$57 million. The discounted cash flow rate of return and return on investment are about 50% and 78% respectively with a discounted payback period of about 2 years. Overall, this plant design is deemed as safe and profitable based on results provided throughout this report.

Assumptions made during the design of this process and are presented in Section 10.1 of this report.

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## 1. PROJECT SCOPE

### 1.1 Problem Statement

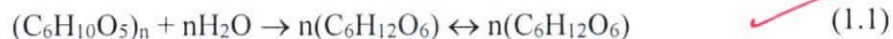
*1<sup>st</sup> tell me what you're doing. What is the problem*

Glucose – fructose syrup (GFS) is a liquid sweetener composed of multiple glucose and fructose chains. It can be obtained from various sources of starch such as corn, wheat, potato, tapioca, etc. GFS has become a staple alternative sweetener from graduated cane sugar in the food and beverage industry, owing to various attributes such as a high sweetness content, its non-crystalline nature, its ability to keep products fresh by maintaining content moisture, etc. GFS obtained from corn starch is generally referred to as high fructose corn syrup (HFCS). HFCS 55 with 55% fructose and HFCS 42 with 42% fructose are the grades that will be produced with this design. Corn gluten feed is also obtained from the purification processes and will be sold to local farmers. HFCS 42 is mainly used in processed and baked goods due to its mild sweetness level while HFCS 55 is used in carbonated drinks and juices because of its high level of sweetness.

Granulated cane sugar has become a relatively expensive sweetener for use in the food and beverage industry, therefore the search for an alternative sweetener is the ultimate goal for these industries. HFCS serves as an appropriate replacement for cane sugar in the food and beverage industry due to it being a relatively cheaper alternative compared to granulated cane sugar. From the preliminary economic analysis of different raw materials, corn starch was selected for use as it was the cheapest.

The production begins when a starch slurry is formed which undergoes three enzymatic reactions (liquefaction, saccharification, and glucose isomerization) with additional purification steps. Liquefaction gelatinizes the slurry using the  $\alpha$ -amylase enzyme, saccharification creates the glucose syrup using the glucoamylase enzyme, and glucose isomerization creates the fructose-glucose ratio in the syrup using the glucose isomerase enzyme. The overall reaction

showing the conversion of corn starch to glucose followed by subsequent isomerization is represented by Equation 1.1 below:



The plant will produce 706 MM lb of HFCS annually that will be sent to the identified consumers 52% will be HFCS 55 and 48% will be HFCS 42. Some proteins, oils, and fibers which constitute corn gluten feed is also derived during this process and do not pose any health or safety threats. They will be separated out and converted to animal feed that can be used by local farmers. There is a high demand for HFCS in the North American food and beverage markets. For this reason, the plant will be located in Asbury, Iowa United States.

Our design basis can be found in Section 11.1 of this report. Our team will submit a final report that summarizes our project by May 4<sup>th</sup>, 2020.

## 1.2 Client Identification and Recognition of Need

The target companies for the final HFCS products are Pepperidge Farm in Pleasant Prairie, Wisconsin and Coca Cola Company in Chattanooga, Tennessee. These companies were selected as potential clients because HFCS is a vital raw material in the production of their respective products. In addition to this, the reputation built by these companies and their longevity as major suppliers of their respective products also guarantee the success of this project in the long run. Asbury, Iowa is an ideal plant location. It is at a reasonable distance from both major clients, and the infrastructures set in place allows for easy transportation so that the quality of the product is maintained before delivery to the aforementioned companies.

HFCS 55 is highly useful in carbonated drinks and juices because of its high sweetness level; it is also favored over sugar because of its cheapness (Hanover 728). Therefore, Coca Cola would use this specific grade for its carbonated drink products. HFCS 42 is mainly used for



canned fruits, sauces, processed foods, and condiments because of its mild sweetness and food preservative properties it offers (Hanover 728). Pepperidge Farm would use this specific grade for preservative and sweetness purposes, for products such as bread, cereal, and granola.

### **1.3 Project Goals and Objectives**

The goal of this project was to design a chemical plant that produces glucose-fructose syrup that would cater to the supply and demand of the product within chemical industries. Our project goals are to develop all major equipment design specifications within our plant, conduct a plant economic analysis, give the final presentation, and create a final report. A Gantt Chart was created to show the project's schedule to achieve these goals as well as the project milestones.

### **1.4 Contemporary Issues and Impact of Project on Society**

#### **1.4.1 Contemporary Issues Relevant to Project**

High Fructose Corn Syrup (HFCS) has become a popularly used sweetener for the food and beverage industry due to it being more cost-effective and easier to handle over refined cane sugar (Tou 1). However, it has gained a bad reputation within public health community over the concerns of rising rate in obesity, diabetes, and other cardiovascular diseases have been attributed to the consumption of foods containing HFCS (Tou 1). The negative news on HFCS is used as a proxy for the relation between HFCS consumption and obesity in the United States (Kennedy 4). Furthermore, the negative news on HFCS is found to have a negative and significant effect on the demand for soft drinks, which is the main driver for the demand of HFCS, but soft drink advertising has more than offset the effect of negative news produced (Kennedy 4).

#### **1.4.2 Potential Impact of Project on Society**

High Fructose Corn Syrup (HFCS) has become the main driver for alternative sweeteners for many products within the food and beverage industry. Sucrose was commonly used before





modified corn syrup in the food and beverage industry (Intelligence 1). The high and fluctuating sugar prices, along with the abundant use of HFCS in the beverage industry, has almost replaced sugar in the beverage industry (Intelligence 1). Our product HFCS 55 was strategic design to have the same relative sweetness as sucrose, so it can easily substitute sucrose in food and beverage industry (Intelligence 1). Same for the other grade HFCS 42 with a lower relative sweetness can easily replace sucrose (Intelligence 1). The plant is located in Asbury, Iowa which is not a very industrialized town. The establishment of this plant here could provide employment to the town locals while not posing a threat to the safety and well-being of these individuals.

### 1.5 Project Constraints

One of the constraints for this project involved the process choices in terms of available production routes, but the main constraint was choosing whether or not to produce the raw material on-site or purchase it especially since there are multiple raw materials that could be used to obtain starch (tapioca, potatoes, corn, beets, etc.). Choosing to purchase the raw material would require narrowing our source of starch to the cheapest source that can produce the amount required for our plant. Some important process conditions to consider for our plant were temperature and pH due to the sensitivity of the enzymes involved in the process. The design and operation temperatures for our equipment had to be feasible for both the functioning of the system and the environment. Stainless steel had to be used for a vast majority of the equipment in order to meet food-handling hygiene specifications and this limited the amount of optimization that could have been performed to reduce equipment cost. Also, additional equipment had to be added to the plant design such as ion exchangers, adsorption columns, and rotary filters to remove waste, mineral ions, and decolorization agents that would diminish the quality of our final product. Standard and codes for designing most equipment were based on the





American Institute of Chemical Engineering (AIChE) regulations. For pressure vessels, the standard and codes used were based on the American Society of Mechanical Engineers (ASME) regulations. Safety and Environmental regulations required for proper plant design had to be based on Occupational Safety and Health Administration (OSHA) and the Environmental Protection Agency (EPA) regulations.

## **2. PROJECT PLANNING AND TASK IDENTIFICATION**

### **2.1 Task Identification and Timeline**

The project was organized into four primary major tasks: Design Specifications, Economic Analysis, Final Presentation Preparation, and the Final Report. These major tasks and their respective subtasks are shown in Table 2.1, along with their timeline. Design specifications had a focus on major equipment sizing and preliminary costing, as well as preliminary optimization which was noted by the individual process efficiency task. On completion of those tasks, converging a simulation of our design could then be accomplished. The economic analysis task utilized the preliminary cost data in the design specification task and expanded on that costing data. It was scheduled to follow the design specification major task for that reason. This section of the project involved the capital cost associated with the major equipment, operating cost, and net present value (NPV) and rate of return on investment (ROROI). Other costing tasks are shown in Table 2.1. Final presentation preparation was the shortest task with about 11 days. Subtasks included an agreed upon finalized design through design optimization and presentation practice. The last major task was the Final Report. This section encompassed compiling data over the span of the whole project timeline and writing a rough draft of the final report.



Table 2.1 Project Task Summary

| Task Name                                        | Duration       | Start              | Finish             |
|--------------------------------------------------|----------------|--------------------|--------------------|
| <b>I. DESIGN SPECIFICATIONS</b>                  | <b>32 days</b> | <b>Thu 1/23/20</b> | <b>Fri 3/6/20</b>  |
| <b>a. Unit Sizing and Preliminary Cost</b>       | <b>27 days</b> | <b>Thu 1/23/20</b> | <b>Fri 2/28/20</b> |
| i. Packed Bed Reactor                            |                |                    |                    |
| ii. Liquid Chromatography Column/Ion Exchange    |                |                    |                    |
| iii. STR'S                                       |                |                    |                    |
| iv. Pumps                                        |                |                    |                    |
| v. Heat Exchangers                               |                |                    |                    |
| <b>b. Individual Process Efficiency</b>          | <b>32 days</b> | <b>Thu 1/23/20</b> | <b>Fri 3/6/20</b>  |
| i. Energy Balance                                |                |                    |                    |
| ii. Refine MEB                                   |                |                    |                    |
| iii. Overall Process Efficiency                  |                |                    |                    |
| iv. Safety Parameters                            |                |                    |                    |
| v. Control Unit for PBR                          |                |                    |                    |
| <b>c. Converge Aspen</b>                         | <b>30 days</b> | <b>Mon 3/2/20</b>  | <b>Fri 4/10/20</b> |
| i. Unit Specifications                           |                |                    |                    |
| ii. Heat Exchangers                              |                |                    |                    |
| iii. Final Simulated Design                      |                |                    |                    |
|                                                  |                |                    |                    |
| <b>II. ECONOMIC ANALYSIS</b>                     | <b>36 days</b> | <b>Mon 2/10/20</b> | <b>Mon 3/30/20</b> |
| i. Major Equipment Capital Cost                  |                |                    |                    |
| ii. Estimated Operating Cost                     |                |                    |                    |
| iii. Plant Logistics                             |                |                    |                    |
| iv. Price for Utilities                          |                |                    |                    |
| v. Price for Transportation and Waste management |                |                    |                    |
| vi. Present Net Value and Investor ROI           |                |                    |                    |
|                                                  |                |                    |                    |
| <b>III. FINAL PRESENTATION PREPARATION</b>       | <b>11 days</b> | <b>Mon 4/13/20</b> | <b>Sat 4/25/20</b> |
| i. Design Optimization                           |                |                    |                    |
| ii. Presentation Practice                        |                |                    |                    |
| iii. Final Practice                              |                |                    |                    |
|                                                  |                |                    |                    |
| <b>IV. FINAL REPORT</b>                          | <b>69 days</b> | <b>Thu 1/23/20</b> | <b>Tue 4/28/20</b> |
| i. Compiling Information in Report               |                |                    |                    |
| ii. Revise Rough Draft                           |                |                    |                    |



## 2.2 Gantt Chart

The data in the Table 2.1 was compiled in the form of a project Gantt chart shown in Figure 2.1. Milestones were noted upon completion of the following tasks: Major Equipment Sizing, Individual Process Efficiency, Converge Aspen, Economic Analysis, Final Presentation Preparation, and the Final Report. Specified task allocation is also noted in Figure 2.1. ✓

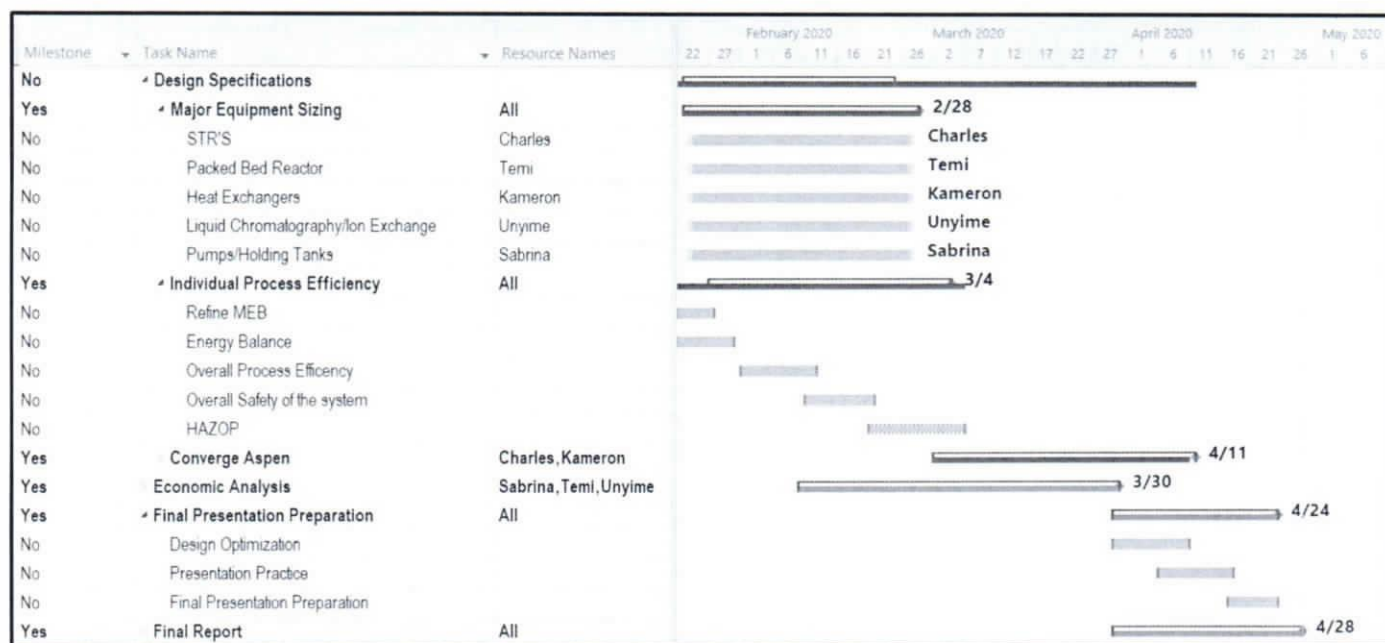


Figure 2.1 Gantt Chart

## 3. OVERVIEW OF THE MANUFACTURE OF GLUCOSE – FRUCTOSE SYRUP

High Fructose Corn Syrup is commonly produced by hydrolyzing starch to yield glucose (dextrose) syrup, and then converting glucose syrup to fructose syrup through isomerization. Using isolation and purification techniques, the concentrations of 42% and 55% fructose can be achieved in the final product syrup (Yuceer 783). Though there are deviations in sources of raw

material starch, the chemistry of producing high fructose syrups generally follows three major reaction steps: liquefaction, saccharification, and isomerization (Johnson 617).

### 3.1 Production Routes

*Good overview*

Glucose-Fructose Syrups can be made by either inversion of sucrose through hydrolysis, or the hydrolysis of starch that could be obtained from a variety of raw material sources such as corn, potatoes, cassava, and wheat (Whitehurst 210).

#### 3.1.1 Starch Hydrolysis

Starch hydrolysis is the breakdown of bonds in the starch molecule using water. This process can be facilitated by the use of acids or enzymes (amylases) (Carr 2443). Acidic hydrolysis gives a lower yield and increased undesired by-products; therefore, enzymatic hydrolysis is more favorable in industrial use (Azmi 265). First, starch which is extracted from the raw material undergoes gelatinization where the starch is broken down with the addition of heat and water, forming a slurry (Johnson 618). Liquefaction describes the process of partial hydrolysis of the starch to yield oligosaccharides like maltose, as well as glucose (Lima 425). This step of hydrolysis is catalyzed using thermostable  $\alpha$ -amylase enzyme and the resulting product generally has a dextrose equivalent amount of 8-12% (Whitehurst 206). In saccharification, glycosidic bonds of the starch molecule are broken down into simple sugars using glucoamylase enzyme as the catalyst (Converti 101). In the case of HFCS, a DE amount reached by saccharification is usually about 95-97% (Whitehurst 210). After hydrolysis, isomerization converts the glucose syrup to fructose. The reaction is catalyzed by glucose isomerase as the reaction enzyme (Barker 101).





### 3.1.2 Sucrose Inversion

Sucrose inversion is the hydrolysis of sucrose to an equimolar mixture of glucose and fructose (Martinez 22). This equimolar mixture is also known as invert sugar which is sent to an enrichment column where the fructose concentration is increased. Any remaining glucose syrup can be subject to isomerization until the desired fructose concentration is achieved. Invertase is the commercial enzyme used for sucrose inversion which is usually carried out in a fixed bed reactor with a strong cation resin (Gehlawat 28). Research showed into the use of immobilized invertase shows successful sucrose hydrolysis (Kilara 166) and suggested operational temperature for the enzyme in the reactor is 55 – 60°C.

## 3.2 Physical and Chemical Properties

Due to HFCS being a complex mixture, specific most chemical properties are not easy to characterize. Section 3.2.1 highlights some of its physical properties while Section 3.2.2 highlights some physical and chemical properties of glucose syrup (corn syrup).

### 3.2.1 Physical Properties of HFCS (OSHA 1996)

- For HFS-42 density (lb/ft<sup>3</sup>): 83.26 (liquid), 59.10 (solid)
- For HFS-55 density (lb/ft<sup>3</sup>): 85.73 (liquid), 65.98 (solid)
- Colorless, odorless liquid

### 3.2.2 Physical and Chemical Properties of Glucose Syrup (FDA, Title 21)

- Molecular Formula: C<sub>6</sub>H<sub>14</sub>O<sub>7</sub>
- Molecular Weight: 198.17 g/mol
- Viscous, odorless, colorless liquid
- Density (g/mL): 1.4



- Freezing/Melting Point: 217-221 °F
- Decomposition Temperature: 217-221 °F
- Solubility: Freely Soluble
- Non-flammable
- Chemical Stability: Stable under normal conditions

*are these really on the same range?*

### 3.3 Handling, Storage and Safety

#### 3.3.1 Handling and Storage

HFCS should be handled with care while properly observing proper industrial hygiene. Appropriate protective equipment should be worn and contact with the eye should be avoided (High Fructose Corn Syrup MSDS). HFCS should be stored at room temperature in a cool and dry place with proper ventilation. The container should be sealed tightly, and the product should be kept away from incompatible materials (NCBE).

Proper handling of enzymes consists of storage at low temperatures in dry environments. Both thermostable  $\alpha$ -amylase and glucoamylase should be stored between 37-41°F, to retain their activity. In that temperature range, thermostable  $\alpha$ -amylase can retain activity for about a year, and glucoamylase for about 6 months (Novozymes). Some enzymes may irritate the skin, eyes and, mucous membranes upon prolonged contact. These enzymes can create easily inhaled aerosols if vigorously mixed or stirred. If spilled the dried enzyme's residue can create dust. This can be a dust explosion hazard if not addressed properly. Also, any spilled enzyme should be flushed away with water to avoid any splashing (Novozymes).



### 3.3.2 Safety

#### 3.3.2.1 EPA, OSHA Regulations and Environmental Impact

The Food and Drug Association (FDA) recognizes HFCS as a generally safe substance, however, some product requirements have been stipulated (FDA, Title 21). Such requirements include:

- Arsenic (as As) content no more than 1 mg/kg
  - Heavy metals (as Pb), not more than 5 mg/kg
  - Lead, not more than 0.1 mg/kg
  - Sulfur dioxide, not more than 0.003 percent
  - Color, within the range specified by the vendor which is primarily colorless
- very good!*

The Occupational Safety and Health Administration (OSHA) regulations on starch handling specify a dust accumulation limit of 1/8<sup>th</sup> of an inch, to lower risk of explosion (OSHA 1996). For this reason, areas nearby any bulk storage of starch must be properly cleaned when approaching this limit. OSHA also recommends limited exposure to the enzyme alpha-amylase used during liquefaction as it has been shown to cause chronic respiratory issues (Brisman 553). For the prevention of respiratory risk, OSHA mandates respirators to be clean and easily accessible following the CFR 1910.134 code (OSHA 1998). ✓

### 3.4 Uses

HFCS is usually named based on the composition of fructose present in the syrup (Lima 425). The three common forms produced industrially are HFCS 42, HFCS 55, and HFCS 90 (Yuceer 783). HFCS 90 is the major product obtained and is further processed to yield HFCS 42 and HFCS 55 which are used in the food and beverage industries as sweeteners (Hanover 729). HFCS 55 is widely used in the production of carbonated soft drinks while HFCS 42 which is not as sweet is generally used in the production of baked goods, noncarbonated beverages, and many

processed foods (Tou 3). When compared to sucrose, HFCS possesses qualities that are beneficial in the food industry. Firstly, it is relatively cheaper than sucrose (Gehlawat 30). Secondly, it has preservative properties because of its high acidity (Parker 72). Thirdly, it is more soluble and does not crystallize in solutions (Hanover 727). In addition to this, it helps to lower the freezing point to retain moisture in certain processed foods (Yuceer 784).

### 3.5 Product Specification

HFCS 42, HFCS 55, and HFCS 90 are the three grades that can be produced; however, HFCS 42 and HFCS 55 are the two products produced and sold by this plant. Both of our products must abide by FDA requirements previously stated (Schenck 18).

### 3.6 Raw Material Preparation

*active, not passive voice.*

Isolating starch within the corn is achieved by a process called wet milling. Corn being the supply of the starch is primarily delivered using rail and truck. The corn, delivered as shelled corn, is sent to receiving pits to be scaled and sampled and is then cleaned to remove foreign solids and dirt. After the corn is cleaned it is moved to a series of steeping tanks causing corn kernels to swell which loosens the contents of the corn by means of soaking the corn in a solution warm water and sulfur dioxide (Rausch 468). Steeped corn is then passed through degerminating mills where the kernel is torn apart exposing the germ, gluten, fiber, and starch of the corn. Liquid cyclones then are used to separate the germ from the gluten, fiber, and starch mixture. In a series of washers, grinders, and screens the fiber can be removed and eventually sold as animal feed. The remaining mixture of primarily starch, gluten, and water is sent to centrifuges to separate gluten and starch, based on varying densities (Ramírez). Lastly, the mixture of starch and water can be further washed and filtered to remove other organics in the



stream. This product slurry contains close to 35% starch and 65% water. This slurry can then be reacted and used to yield glucose syrup for the HFCS production (Hanover 725).

## 4. PROCESS SELECTION

### 4.1 Market Analysis and Trends

Four main companies control about 85% of the \$2.6 billion U.S. HFCS Industry (Parker 72). The four main companies are Archer Daniels Midland, Cargill, Staley Manufacturing Co, and CPC International. An analysis of the supply and demand in the high fructose corn syrup market was obtained based on results gathered by Dr. Lyn Kennedy of Louisiana State University and Dr. Garcia-Fuentes of Midwestern State University (Garcia-Fuentes). The study began ran from 1992 to 2013, and currently, the market supply and demand are decreasing every year (Garcia-Fuentes). For instance, from 2017 to 2018 the total U.S production of all HFCS fell from 8.2 to 8 million short tons a year. In parallel, deliveries of HFCS in the U.S decreased from 6.9 to 6.8 million short tons from 2017 to 2018. However, the average sale price is steadily increasing and the demand for HFCS is expected to be high for at 20 years (USDA). The analysis describes how events such as negative news and the soft drink market are major factors that affect the demand for HFCS. Figure 4.1 shows that the HFCS and soft drink markets almost mirror each other. This is due to the enormous use of high fructose corn syrup in the soft drink market. Around 75% of HFCS production goes into the soft drink market per the USDA and HFCS 55 is used more than HFCS 42. Therefore, it is recommended that more HFCS 55 should be produced from a designed plant.

✓ So then why  
percentage Farm?



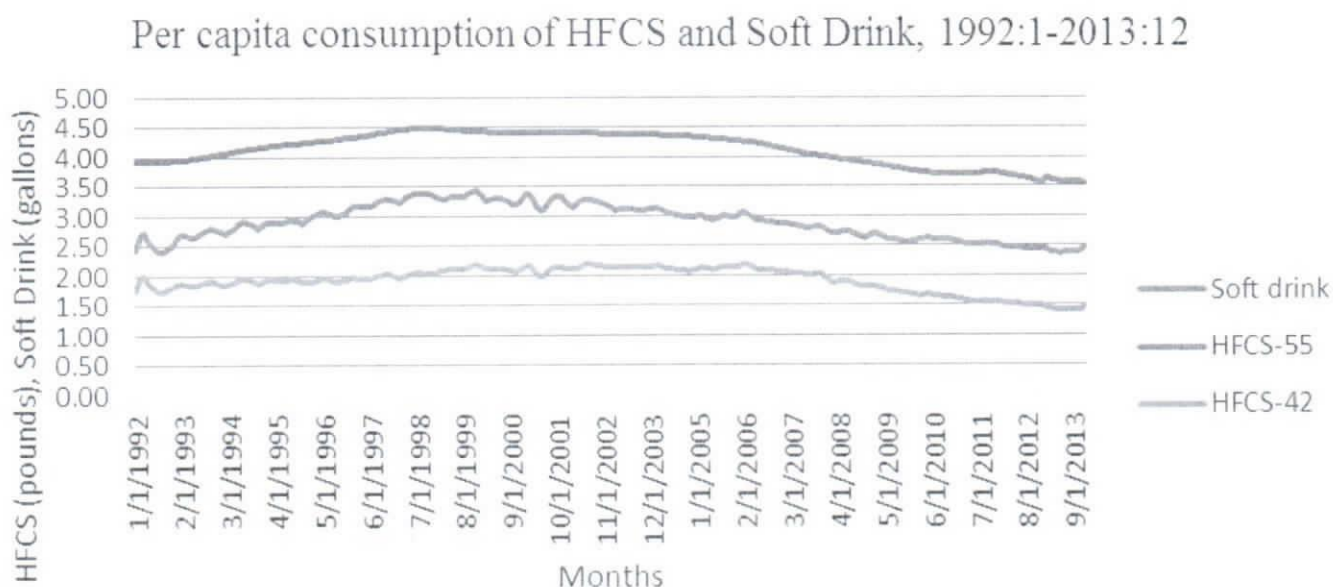
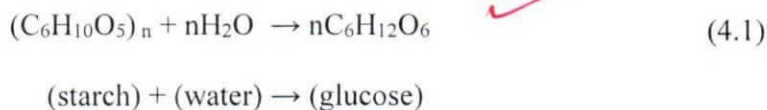


Figure 4.1 HFCS and Soft Drink Consumption Trend in the U.S

## 4.2 Reaction Routes to Producing Product

### 4.2.1 Enzymatic Starch Hydrolysis Followed by Glucose Isomerization

For starch hydrolysis, water molecules break down the polysaccharide into long glucose chains using the  $\alpha$ -amylase enzyme. This long chain is further broken down into smaller glucose units using the glucoamylase enzyme. The glucose syrup obtained is purified before being isomerized to obtain some fructose. The immediate product of this reaction is HFCS 42 which when blended with HFCS 90 (obtained through HFCS 42 enrichment) gives HFCS 55. The overall reaction for the conversion of starch to glucose is shown in Equation 4.1 below where  $n$  is from 50 to thousands:

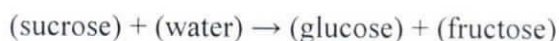
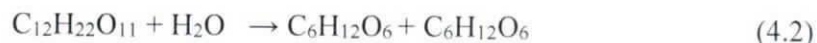






#### 4.2.2 Enzymatic Sucrose Inversion Followed by Fructose Enrichment

With sucrose inversion, sucrose is broken down to a 50:50 glucose-fructose mixture using water and in the presence of the invertase enzyme. The fructose obtained in this resulting solution can further be enriched to give the desired concentration. The overall reaction for sucrose inversion to invert sugar is represented by Equation 4.2 below:



#### 4.3 Process Screening using Theoretical Economic Indicator

*Good!*

A theoretical economic indicator for the main reaction routes was performed to give a preliminary idea of the gross profit that could be attained depending on the reaction route selected. The results are shown below in Table 4.1 and Table 4.2

##### Sucrose Theoretical Economic Indicator

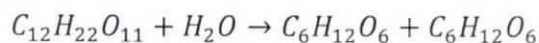


Table 4.1 Analysis for HFCS Using Sucrose

|         | Sucrose | Water | HFCS    |         |
|---------|---------|-------|---------|---------|
|         |         |       | HFCS-42 | HFCS-55 |
| lb/mole | 1       | 1     | 1       | 1       |
| MW      | 342     | 18    | 360     | 360     |
| lb      | 342     | 18    | 360     | 360     |
| lb/HFCS | .95     | .05   | 1       | 1       |
| ¢/lb    | 59.6    | 1     | 35.21   | 41.23   |

$$\text{Gross Profit} = 35.21(1) - 59.6(.95) - 18(0) = -21.41 \text{ ¢/lb HFCS 42\%}$$

$$\text{Gross Profit} = 41.23(1) - 59.6(.95) - 18(0) = -15.39 \text{ ¢/lb HFCS 55\%}$$

##### Starch Theoretical Economic Indicator

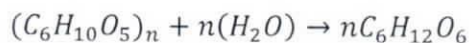


Table 4.2 Analysis for HFCS Using Starch

|         | Starch | Water | HFCS    |         |
|---------|--------|-------|---------|---------|
|         |        |       | HFCS-42 | HFCS-55 |
| lb/mole | 2      | 2     | 1       | 1       |
| MW      | 162    | 18    | 360     | 360     |
| lb      | 324    | 36    | 360     | 360     |
| lb/HFCS | .9     | .1    | 1       | 1       |
| ¢/lb    | 6.26   | 0     | 35.21   | 41.23   |

$$\text{Gross Profit} = 35.21(1) - 6.26(.9) - 18(0) = 29.58 \text{ ¢/lb HFCS 42\%}$$

$$\text{Gross Profit} = 41.23(1) - 6.26(.9) - 18(0) = 35.60 \text{ ¢/lb HFCS 55\%}$$

#### 4.4 Process Comparison and Selection

The HFCS industry is dominated by the starch hydrolysis route. Based on the results of the theoretical economic indicator, starch hydrolysis was the more viable reaction route for both HFCS 42 and HFCS 55 because the sucrose inversion route gave negative profit values. In selecting the raw material to be used for production, two factors played a major role. The first was accessibility and the second profitability of raw material in the U.S food and beverage market. In the U.S, our target market, the mid-west is host to several major producers of corn starch which is mostly used due to its abundance near the target market as well as its cheapness relative to alternative starch sources (Parker 74). The cost of corn starch is 6.26 cents per pound compared to sucrose at 59.6 cents per pound. Also, from the indicator, starch has the potential to produce profit for both grades of HFCS. Therefore, a hydrolysis process using starch as the raw material was the most suitable option and was selected for this project.

*You only use economic considerations for process selection??*



## 5. PROCESS DESCRIPTION

### 5.1 Block Flow Diagram

The block flow diagram for the production of HFCS 42 and HFCS 55 from corn starch is represented in Figure 5.1 below.

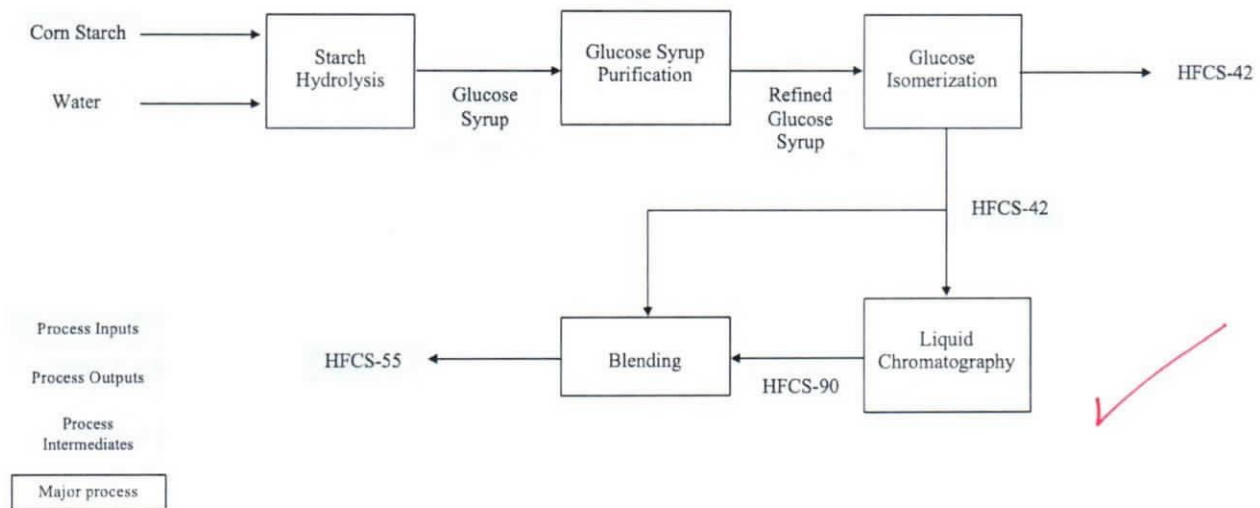


Figure 5.1 Block Flow Diagram

### 5.2 Process Description

The process involved in the production of high fructose corn syrup (HFCS) can be divided into three main processes: hydrolysis, purification, and isomerization. These three stages encompass the entire process and are comprised of various single units. A detailed description of the entire process is described below:

#### Hydrolysis

A feed of dry corn starch is mixed with water in a stirred tank to make starch slurry containing between 30% to 35% solid starch to allow the slurry to be easily pumped and prevent clogging in the pipes. A positive displacement pump is used to move this slurry because it has a high viscosity of about 1300 cP (List of Typical Viscosities). The starch slurry obtained from the tank is sent to a jet cooker which uses steam to gelatinize the slurry for 5-10 minutes (Derez).

The steam used in this process is culinary steam and is more hygienic than plant steam because it contains FDA approved boiler chemicals. After this, liquefaction is done by mixing  $\alpha$ -amylase with the slurry for 2 hours to convert a high percentage of starch to a dextrin hydrolysate with a dextrose equivalent (DE) of 10% and a 50% w/w solid solution. The glucose slurry is then cooled in preparation for saccharification. Glucoamylase is fed into the next stirred tank reactor to complete the breakdown of starch into dextrose (glucose). Saccharification is the longest phase in the process with a duration of 48-96 hours (Carr 2443). The starch hydrolysis process is shown in Figure 5.2 below.

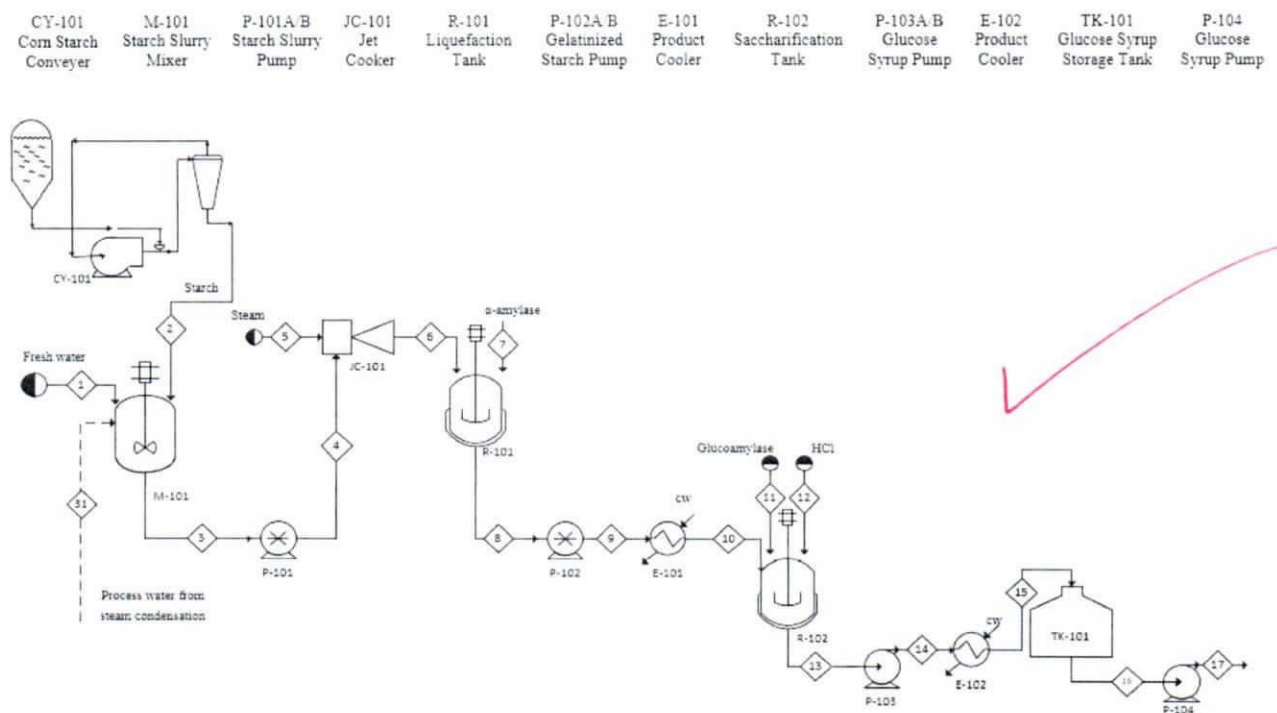


Figure 5.2 Process Flow Diagram for Starch Hydrolysis

### Syrup Purification

The glucose syrup obtained is sent through a series of purification stages. First, it goes through a rotary filter to remove proteins, fibers, and lipids. Then it passes through a carbon filter to remove ash, a mixture of salts obtained from processed corn. Lastly, a 50:50 solid to liquid





product goes through an ion-exchange column to remove unwanted ions. After purification, the syrup is sent into a mixer where sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and magnesium sulfate ( $\text{MgSO}_4$ ) are added to increase the pH and ensure enzyme stability respectively in preparation for isomerization. The product from the mixer goes into an evaporator where steam is used to concentrate glucose syrup into an 80% w/w solution. The vapor that leaves the evaporator goes into a condenser and is condensed into liquid water that is recycled into the first stirred tank. The syrup purification process is shown in Figure 5.3 below.

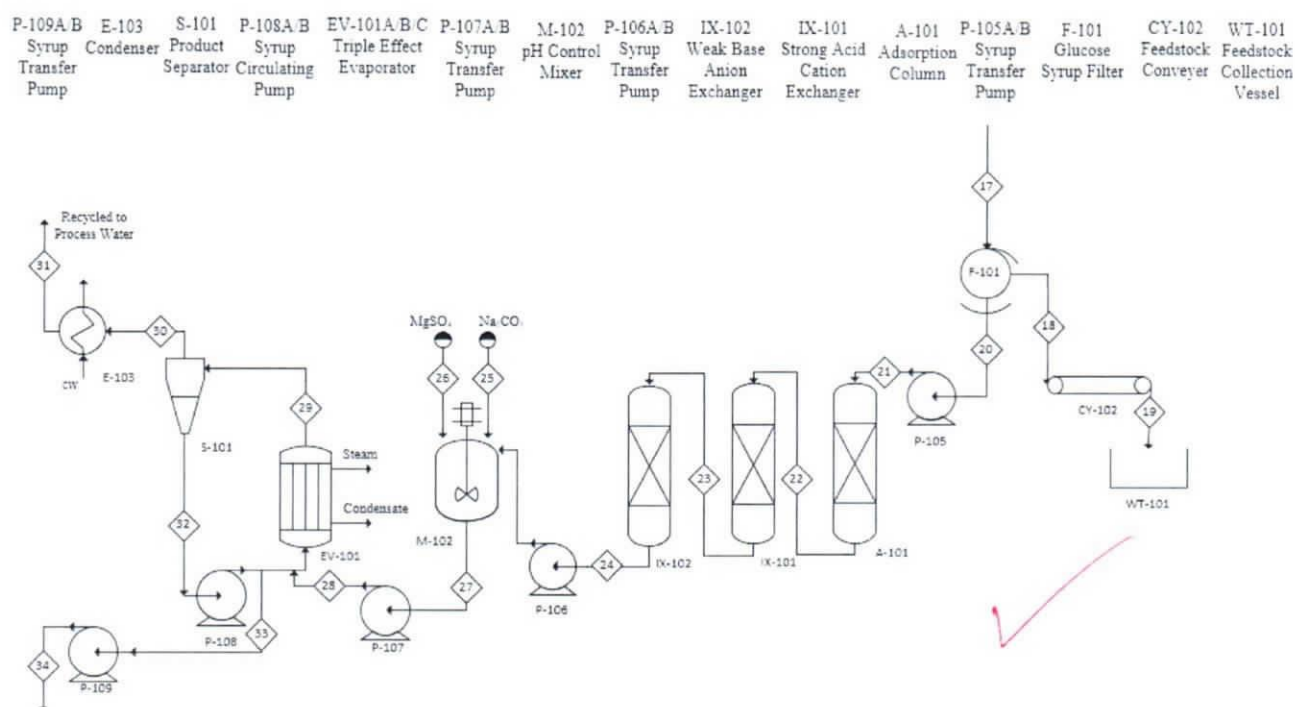


Figure 5.3 Process Flow Diagram for Syrup Purification

### Isomerization and Fructose Enrichment

The purified liquid syrup leaves the evaporator at a temperature of 121°F and is pumped into a jacketed packed bed reactor (PBR); the purpose of the jacket is to supply heat and maintain a temperature of 140°F in the reactor for isomerization to take place. Isomerization

occurs for about 4 hours, as glucose isomerase converts the glucose syrup to HFCS 42 (Venkatasubramanian 146). The HFCS 42 product is split into two streams, one stream is sent into storage tanks while the other is passed through a chromatography column to concentrate it to HFCS 90. The two grades of HFCS are then mixed to give a final HFCS 55 product. The glucose isomerization and syrup enrichment process are shown in Figure 5.4 below.

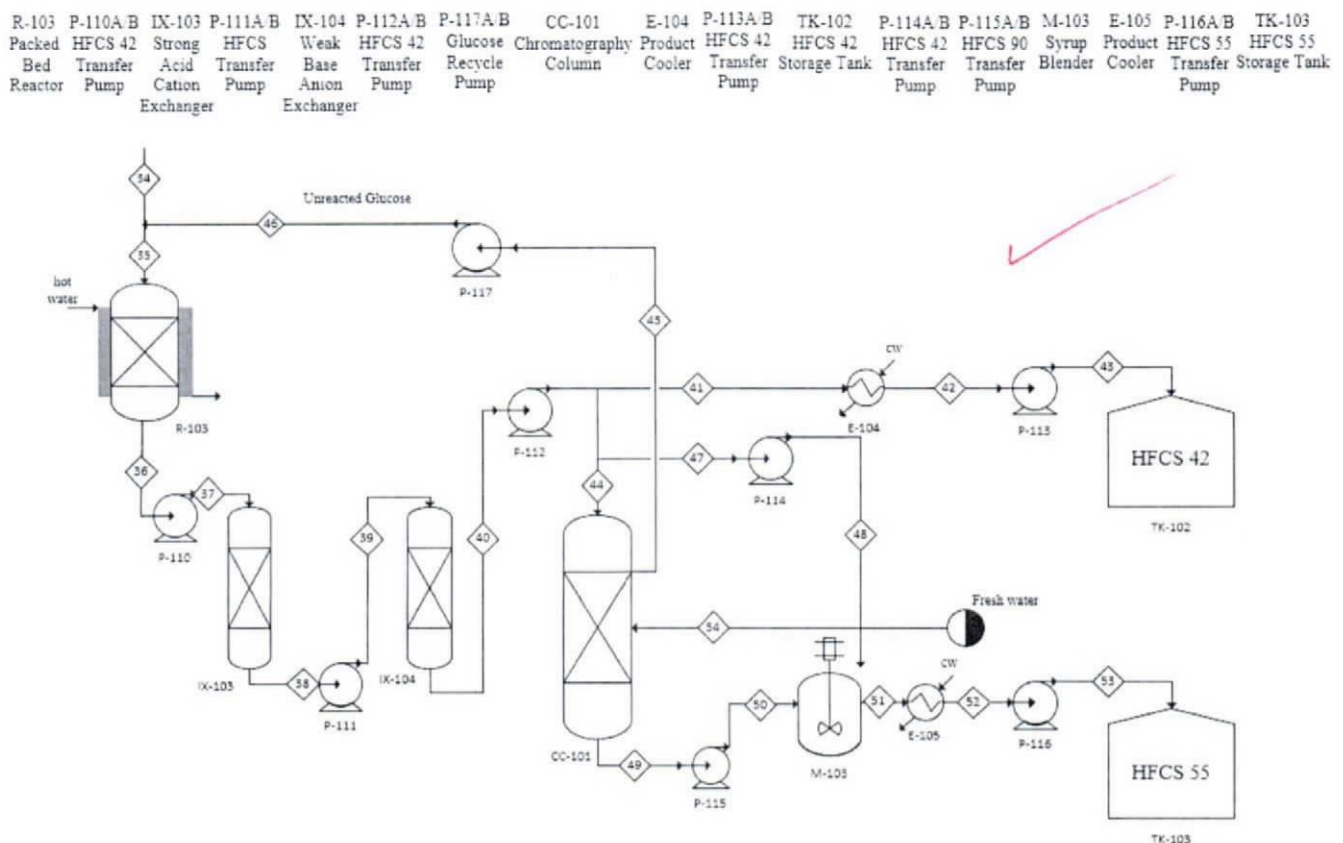
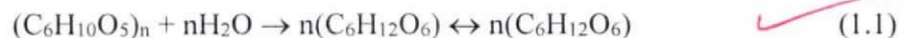


Figure 5.4 Process Flow Diagram for Fructose Enrichment

### 5.3 Process Chemistry

#### 5.3.1 Reaction Stoichiometry

The overall reaction equation for the conversion of corn starch to HFCS is represented by Equation 1.1.







For the first reaction, the stoichiometric coefficients for  $\text{H}_2\text{O}$  and  $\text{C}_6\text{H}_{12}\text{O}_6$  are equal and dependent on the number of glucose monomers that make up the starch chain to be hydrolyzed. For the second reaction, both  $\text{C}_6\text{H}_{12}\text{O}_6$  isomers have equal stoichiometric coefficients (1:1).

### 5.3.2 Kinetics and Rate Equations

#### Hydrolysis Reactions

Hydrolysis is a reaction in which water reacts with a given substrate. For HFCS production the substrate used is corn starch. The reaction rate is highly dependent on the efficiency of the enzyme used. For that reason, two different catalysts are used to maximize conversion and reaction rate,  $\alpha$ -amylase and glucoamylase, which splits hydrolysis into two major steps: Liquefaction and Saccharification.

#### **Liquefaction**

The process of liquefaction hydrolyzes swelled starch granules by cleaving  $\alpha$ -1,4-glycosidic linkages to achieve the 8-12% DE product. The reaction is best characterized as exergonic, meaning that  $\Delta G$  is negative, making the reaction spontaneous (Bismark 113). This biological reaction can be catalyzed with varying enzymes, classified as either endoenzymes or exoenzymes depending on how they were derived (Novozymes). This distinction is important as enzymes in hydrolysis can greatly affect the overall reaction kinetics of the system. This can be demonstrated by the substrate-enzyme mechanism shown in chemical Equations 5.1, 5.2 and 5.3.



This mechanism gives a reaction rate equation that relates the concentration of substrate ( $C_S$ ), maximum reaction rate when the substrate is saturated with the enzyme ( $v_{max}$ ), and the

concentration of substrate needed to half of the  $v_{max}$  value ( $k_m$ ). This relationship is shown below in Equation 5.4 and was used to determine the reaction rate of our system.

$$r_p = \frac{v_{max}(C_S)}{k_m + C_S} \quad (5.4)$$

For HFCS hydrolysis, starch serves as the substrate in the system. The concentration was found based upon converting the calculated mass flow rate to the molar flow rate and dividing the value by the calculated volumetric flow. The concentration of starch was roughly 6.98 mol/L. The enzyme used for our process is  $\alpha$ -amylase derived from *Bacillus licheniformis*, but for a more accurate  $k_m$  value a *Pyrococcus furiosus*  $\alpha$ -amylase was used (Rollings 1481). The degree of deviation from reaction conditions of our system, such as optimum pH and temperature, warranted this change. The  $k_m$  value was approximately 0.52 M. Using that value,  $v_{max}$  could be solved for using a slope value ( $k_m/v_{max}$ ) of a Lineweaver Burke plot of starch hydrolysis. The slope value was 2.58 and  $v_{max}$  was solved to be 0.2 M. With the values of  $v_{max}$ ,  $k_m$ , and  $C_S$ , the reaction rate was solved to be 0.188 M/s.

### Saccharification

To achieve higher concentrated amounts of glucose product (greater than 95% DE), the saccharification step of hydrolysis has to occur. This is necessary for HFCS production. Saccharification breaks down amylose and amylopectin chains through cleavage of both  $\alpha$ -1,4 and  $\alpha$ -1,6 bonds to yield dextrans and maltodextrans. This reaction step can be modeled as a pseudo 1<sup>st</sup> Order based upon the limited and disproportionate amount of water concentration active in the reaction (Butterworth 1295), compared to the concentration of broken-down starch substrate (amylose and amylopectin). The method for modeling kinetics for saccharification could not be achieved in the same way liquefaction was, due to varying data at our disposal. So,



the 1<sup>st</sup> Order Batch Reaction equation, shown in Equation 5.5, was used to relate reaction time (t), conversion (X), and k-constant values (k).

$$t = \frac{1}{k} \ln \left( \frac{1}{1-X} \right) \quad (5.5)$$

An optimization curve shown in Figure 5.5 was used to obtain the reaction time and conversion values to be used in Equation 5.5. Using the same figure (Figure 5.5) enzyme dosage amount, chosen for our system, was 0.5/1000 kg of DS to minimize reaction time but also maximize the conversion of glucose.

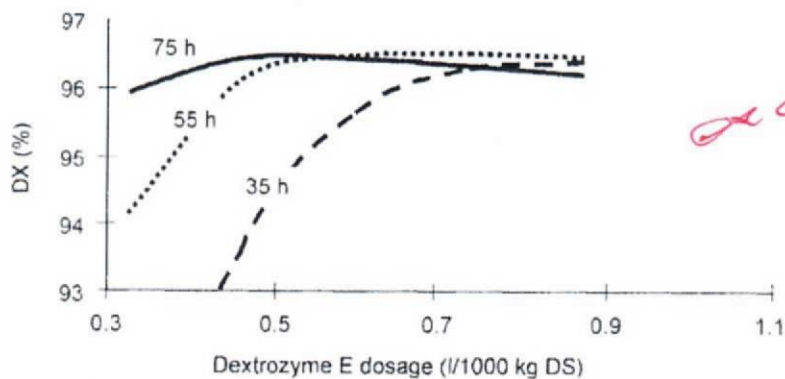


Figure 5.5 Conversion to Dextrose (%) vs Enzyme Dosage (Glucoamylase)

To solve for the k-constant value the reaction times 35, 55, and 75 hours with their respective conversion values of 94.3, 96.2, and 96.3% were used. Those values were chosen due to correspondence with our selected dosage amount. Using Equation 5.5, k-constant values could be calculated, and the results of their change with respect to time can be seen in Figure 5.6. ✓

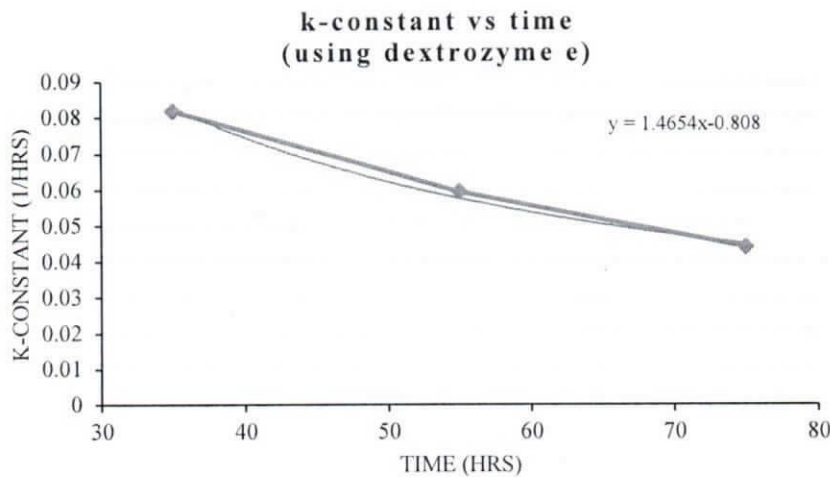


Figure 5.6 k-constant values vs reaction times at (0.5/1000kg of DS)

The most optimum reaction time given our dosage was 55 hours, and the respective k-constant value is 0.06M/hr. Because the behavior of hydrolysis is pseudo 1<sup>st</sup> order the reaction rate equation can also be depicted as 1<sup>st</sup> order, as shown in Equation 5.6.

$$-r_A = kC_A \quad (5.6)$$

Solving for reaction rate could now be achieved given the known k-constant value and concentration of substrate (A). Upon calculating with the assumption of 10% loss (Kodoma 988) in mass from starch substrate, the reaction rate was about 0.342M/s.

#### 5.4 Product to Storage

Stainless steel tanks are the recommended storage tanks used to contain the final products of HFCS 42 and HFCS 55 before they are transported to their respective consumers. They are sized to be large enough to store 3-6 days<sup>1</sup> worth of syrup and the temperature in the tanks should not exceed 118°F (National Sugar Marketing).





## 5.5 Material Balances

### 5.5.1 Basis of Calculations

All calculations were made using English units of pound per hour as the flowrate for each stream. A typical HFCS plant capacity of 1000 metric tons per day was used as the basis for determining the output streams of HFCS 42 and HFCS 55. 46,000 lbs/hr of HFCS 55 and 43,000 lbs/hr of HFCS 42 were used for calculation and determined using the assumptions presented in Section 10.1. The sugar compositions of the product streams were to emulate that of commercial-grade HFCS; hence, they were known. Given these values, calculations were made in a reverse manner until the initial process stream values were obtained.

### 5.5.2 Unit Descriptions and Material Balance

Calculations for the material balance for components in each stream were made for all the units and are shown below with a description of each unit. All the major equipment that are in direct contact with the syrup is made of high-grade stainless steel. In the food processing industry, stainless steel is the most important type of steel used in direct contact with food because of its ductility and high resistance to corrosion. (Saravacos 57).

#### M-101

This is a vertical mixing tank with a volume of 758 ft<sup>3</sup> and a residence time of 10 minutes. Starch slurry is made in the tank by mixing corn starch at 77°F with water. The starch is mixed for several hours with internal agitators until a thick slurry is attained. The pH of the slurry made is 6.5. The stirred tank is made of Stainless Steel 316 and has a bare cost module of \$38,225. See page 49 for the unit specification sheet.

#### P-101

This is a carbon steel progressive cavity pump. It is a type of positive displacement pump that is used for high viscosity fluids. It moves 10,302 gallons of glucose slurry per hour, generating 8 ft



of pump head. Despite its high cost of maintenance, the advantage of using this pump is that the same volume of slurry is pumped at a constant rate and this prevents clogging in pipes. It consumes 1.17 kW electrical power and has a bare module cost of \$29,600. See page 50 for the unit specification sheet.

#### **JC-101**

This is a horizontal stainless-steel jet cooker that provides steam at 105°F needed for gelatinization by steam injection. Gelatinization converts the starch to thick gel and prepares it for liquefaction. Culinary steam is introduced to the jet cooker at a pressure between 10-12 bar. Steam is a useful heating utility and is favored above other process heating methods because the temperature at which the heat is released can be controlled by the pressure of the steam. The starch solution leaving the jet cooker contains 20% w/w solids. The unit has a bare module cost of \$1,816. See page 51 for the unit specification sheet.

#### **R-101**

This is a stainless steel 316 stirred tank reactor for the liquefaction of starch. Gelatinization of the starch occurs for 5-10 mins at high temperatures. A 20% w/w solid solution enters the STR at a pH of 6.5 and  $\alpha$ -amylase containing  $\text{Ca}^{2+}$  (with a concentration between 20-150 ppm) is fed to the slurry to break down the starch molecules into large glucose chains. Seven reactors are operated in series each with a volume of 1069 ft<sup>3</sup>. Flat blade agitators are used for the continuous mixing at an operating pressure of 14 psi. The unit has a bare module cost of \$1,575,000. See page 52 for the unit specification sheet.

#### **P-102**



This is also a carbon steel progressive cavity pump. The glucose slurry still has a high viscosity of about 600cP. The pump head generated is 8ft and the amount of power consumed is 1.17kW. The unit has a bare module cost of \$29,601. See page 52 for the unit specification sheet.

#### **E-101**

This is a shell and tube heat exchanger responsible for cooling the glucose slurry from 221°F to 140°F in preparation for saccharification. It has a heat transfer area of 381 ft<sup>2</sup> and the material of construction is stainless steel. A heat duty of 6.0e6 is required and it has a heat transfer coefficient of 150 Btu/hr-ft<sup>2</sup>-°f. The unit has a bare module cost of \$150,093. See page 54 for the unit specification sheet.

#### **R-102**

R-102 is a stainless-steel stirred tank reactor. 29 reactors are arranged in series each with a volume of 7,063 ft<sup>3</sup>. For saccharification to occur the pH must be at 4.5, HCl is added to decrease the pH. This unit involves a feedforward control process that measures the pH of the incoming slurry. A pH sensor is used on the inlet side of the CSTR to signal chemical pumps to feed hydrochloric acid (HCl) into the reactor to maintain a pH level of 4.5. Glucoamylase is added to break the glucose chain into monomers; the glucoamylase used is made from *Aspergillus niger*. The glucose syrup leaving the reactor has a DE of 95% and leaves as a 50% w/w solid solution. Saccharification completes the breakdown of starch into dextrose and it occurs for a period of 24 to 72 hours. The bare cost module for this unit is \$34,800,800. See page 55 for the unit specification sheet.

#### **P-103**

This is a carbon steel centrifugal pump used to move glucose syrup into the storage tank. It moves 9,246 gallons of glucose syrup per hour and consumes 2kW of electrical power. It has a

bare module cost of \$13,475. The viscosity of the glucose syrup decreases after saccharification and the pumps used to move the glucose syrup after this stage are regular centrifugal pumps. The unit specification section gives all the details of the other pumps used in this process. See page 56 for the unit specification sheet.

#### **E-102**

This is a stainless-steel shell and tube heat exchanger for cooling glucose syrup to 77°F for storage in the tank. The syrup must be cooled to this temperature to avoid microbial growth in the tank. See page 57 for the unit specification sheet.

#### **TK-101**

This is a stainless storage tank that stores 3 days' worth of liquid glucose syrup. Two storage tanks will hold 9,245 gallons each of glucose syrup at 14 psi. The purpose of this tank is to hold the syrup that is being made in the second STR during saccharification. Since this process takes about 72 hours the glucose syrup must be stored until the saccharification process is completed. The stored syrup is what is pumped into the next unit to begin continuous production while another batch of glucose syrup is being made in the second STR. The bare cost module for the unit is \$2,310,540. See page 58 for the unit specification sheet.

#### **F-101**

This is a 304L stainless steel rotary vacuum filter with a precoat discharge. It is a separation device that removes waste products from the syrup through a vacuum mechanism. The filter has a capacity of 200 lbs/hr.ft<sup>2</sup> and a filtration surface area of 729 ft<sup>2</sup>. The waste particles are scraped off with a knife attached to the filter. About 14578 lbs of the filter cake are separated per hour. The filter cake obtained is known as corn gluten feed and it would be sold to local farmers as



feedstock. The unit has a bare module cost of \$908,107. See page 60 for the unit specification sheet.

#### A-101

This is an adsorption column made of stainless steel and is used in the decolorization step of the syrup purification process. The function of this unit is the removal of color-forming components like hydroxymethylfurfural (HMF) and some ions. The unit is packed with DOWEX OPTIPORE SD-2 adsorbent which is an effective alternative to traditional activated carbon systems. For this process, it is assumed that all the ash is removed in this unit. Two adsorption columns are used for this unit each with a volume of 390 ft<sup>3</sup>, a height of 10.86 ft, and a diameter of 6.76 ft. The bare model cost for this unit is \$187,450. See page 62 for the unit specification sheet.

#### IX-101

This is a strong acid cation exchanger made of stainless steel and is used in the deashing step of the syrup purification process. The unit is packed with DOWEX Monoshpere 88 resins which have applications in HFCS purification. The function of the cation resins is the removal of mineral ions such as Na<sup>+</sup>, K<sup>+</sup>, Fe<sup>2+</sup>, Mg<sup>2+</sup>, and Ca<sup>2+</sup> from the glucose syrup. This unit is comprised of two cation exchangers each operated in series with an anion exchanger. The vessel volume is 113 ft<sup>3</sup>. The bare module cost for both exchangers is \$102,652. See page 63 for the unit specification sheet.

#### IX-102

This is a weak base anion exchanger made of stainless steel and is also used in the deashing step of the syrup purification process. The unit is packed with DOWEX Monoshpere 88 resins which have applications in HFCS purification. The function of the cation resins is the removal of mineral ions such as NO<sup>3-</sup>, SO<sub>4</sub><sup>2-</sup>, and Cl<sup>-</sup> from the glucose syrup. Two anion exchangers are also





used for this unit; each anion exchanger is arranged directly after a cation exchanger in series. The vessel volume calculated for the first and second exchangers is 935 ft<sup>3</sup>. Both anion exchangers have a bare module cost of \$379,368. See page 64 for the unit specification sheet.

#### **M-102**

M-102 is a vertical, stainless-steel mixing tank with a volume of 186 ft<sup>3</sup> and a residence time of 10 minutes. The tank is continuously stirred by internal agitators and uses 0.04kW of electricity. A pH sensor is also used at the inlet of the mixer to signal pumps to feed Na<sub>2</sub>CO<sub>3</sub> into the mixer to maintain the pH at 7.5. MgSO<sub>4</sub> is added to ensure enzyme stability of the glucose isomerase used in the isomerization unit. The unit has a bare module cost of \$144,470. See page 66 for the unit specification sheet.

#### **EV-101**

This is a stainless-steel forced circulation evaporator with a residence time of 25 minutes. It is operated as a forward-feed triple effect evaporator with an average area of 1421 ft<sup>2</sup> for each effect. Steam enters the evaporator at 248°F to vaporize water from the glucose syrup. The glucose syrup leaves the evaporator at a temperature of 121°F. The average heat duty required for concentrating the syrup in each effect is 1.6e7 Btu/hr with a steam economy of 2.25. The bare module cost for the unit is \$6,690,000. See page 68 for the unit specification sheet.

#### **E-103**

This is a carbon steel counter-current barometric condenser with a heat load of 2.0e7. The water vapor enters at 111°F to be condensed into a liquid. The water obtained is at room temperature and is recycled into the first stirred tank. 540 pounds of water is consumed for every pound of vapor that is condensed. The bare cost module for the unit is \$120,624. See page 69 for the unit specification sheet.





### **R-103**

This is a jacketed packed bed reactor (PBR) for isomerization. This unit has 14 reactors running in parallel each with a volume of 477 ft<sup>3</sup>. Glucose isomerase enzyme is used to convert glucose syrup to HFCS 42. The molarity of Mg<sup>2+</sup> needed for enzyme activation is 0.0004 M. The HFCS 42 product leaving this unit has a 75:25 solid to liquid weight percentage. The orientation of the reactor is vertical, and the material of construction is Stainless Steel 316. The pressure drop across the reactor is 2 psi and the heat duty required for heating is 34639 Btu/hr. The bare cost module for the unit is \$5,149,200. See page 71 for the unit specification sheet.

### **IX-103**

This is a strong acid cation exchanger made of stainless steel and is used in the deashing step of the syrup purification process. The unit is packed with DOWEX Monosphere 88 resins which have applications in HFCS purification. The function of the cation resins is the removal of Na<sup>+</sup>, Mg<sup>2+</sup>, and Ca<sup>2+</sup> from the HFCS 42. This unit is comprised of two cation exchangers each operated in series with an anion exchanger. The vessel volume is 56 ft<sup>3</sup>. The bare module cost for both exchangers is \$81,600. See page 73 for the unit specification sheet.

### **IX-104**

This is a weak base anion exchanger made of stainless steel and is also used in the deashing step of the syrup purification process. The unit is packed with DOWEX Monosphere 77 resins which have applications in HFCS purification. The function of the cation resins is the removal of mineral ions such as CO<sub>3</sub><sup>2-</sup> and SO<sub>4</sub><sup>2-</sup> from the HFCS 42. Two anion exchangers are also used for this unit; each anion exchanger is arranged directly after a cation exchanger in series. The vessel volume calculated for the first and second exchangers is 236 ft<sup>3</sup>. Both anion exchangers have a bare module cost of \$158,100. See page 74 for the unit specification sheet.

### **Split point**

This point is before the chromatography column. Half of the HFCS 42 produced goes straight to storage and the other half of the HFCS 42 goes through this point and is further split into the chromatography column and a mixer.

### **CC-101**

This is a stainless-steel chromatography column that increases the fructose concentration in the syrup. 18.6% of the HFCS 42 goes into the chromatography column and is enriched to HFCS 90 before it is sent into the mixer. The unit is packed with DOWEX Monosphere 99 resins in the  $\text{Ca}^{2+}$  form which has applications in chromatographic separation of HFCS. This unit is designed as a simulated moving bed and has twelve fixed bed chromatography columns in series with two inlet and two outlet streams. The length of the column is 9 ft with an inner diameter of 3 ft. The unit has a bare module cost of \$380,800. See page 77 for the unit specification sheet.

### **M-103**

This is a stainless- steel mixer where HFCS 42 and HFCS 90 are mixed to give HFCS 55. The amount of HFCS 42 coming from the split point into the mixer is 81.4%. The final HFCS 55 product sent into the storage vessels has a 75:25 solid to liquid weight percentage. The volume of the mixer is 36 ft<sup>3</sup> and it has a residence time of 10 minutes. Internal agitators are used for continuous stirring and they use 0.32 kW of electricity. The bare cost module for this unit is \$101,907. See page 82 for the unit specification sheet.

### **E-104 and E-105**

These are shell and tube heat exchangers that cool HFCS 42 and HFCS 55 respectively before they are stored in tanks. They are made of stainless steel and cool down the syrup to 77°F at 14.7



psi. A heat duty of  $1.7 \times 10^6$  is required and they both have a heat transfer coefficient of 150 Btu/hr-ft<sup>2</sup>-°F. The unit has a bare module cost of \$132,664. See pages 83 and 84 for the unit specification sheet.

### **TK-102 and TK-103**

These are storage tanks that hold 3 days' worth of HFCS products. A total of 29 storage tanks are used to hold HFCS 42 while 30 storage tanks are used to hold HFCS 55. The bare module cost for each tank unit is \$2,320,00 and \$2,400,000 respectively. See pages 85 and 86 for the unit specification sheet.

### **5.5.3 Degrees of Freedom Analysis**

To ascertain that stream calculations could be made, a degree of freedom analysis (DOF) was performed for each unit. These calculations for the major units in each section are shown below. If the DOF was greater than 0, specifications discussed in Section 10.1 were made.

Table 5.1 Degrees of Freedom Analysis for Hydrolysis Step

|                    | Mixer 1 |   | Jet Cooker |   | STR 1 |   | STR 2 |   |
|--------------------|---------|---|------------|---|-------|---|-------|---|
| No. of Variables   |         |   |            |   |       |   |       |   |
| Stream Variables   | 7       |   | 7          |   | 7     |   | 8     |   |
| Chemical Reactions | 0       |   | 0          |   | 1     |   | 1     |   |
| No. of Equations   |         |   |            |   |       |   |       |   |
| Flows              |         | 0 |            | 0 |       | 0 |       | 0 |
| Stream Composition |         | 1 |            | 1 |       | 1 |       | 0 |
| System Performance |         | 0 |            | 1 |       | 0 |       | 0 |
| Material Balances  |         | 3 |            | 3 |       | 5 |       | 4 |
| Sum                | 7       | 4 | 7          | 5 | 8     | 6 | 9     | 4 |
| DOF                | 3       |   | 2          |   | 2     |   | 5     |   |

Table 5.2 Degrees of Freedom Analysis for Purification Step

|                    | Rotary Filter |   | Adsorption Column |   | Ion Exchangers |   |
|--------------------|---------------|---|-------------------|---|----------------|---|
| No. of Variables   |               |   |                   |   |                |   |
| Stream Variables   | 8             |   | 6                 |   | 6              |   |
| Chemical Reactions | 0             |   | 0                 |   | 0              |   |
| No. of Equations   |               |   |                   |   |                |   |
| Flows              |               | 0 |                   | 0 |                | 0 |
| Stream Composition |               | 1 |                   | 0 |                | 0 |
| System Performance |               | 1 |                   | 0 |                | 0 |
| Material Balances  |               | 4 |                   | 3 |                | 3 |
| Sum                | 8             | 6 | 6                 | 3 | 6              | 3 |
| DOF                | 2             |   | 3                 |   | 3              |   |

Table 5.3 Degrees of Freedom Analysis for Isomerization and Enrichment Step

|                    | PBR |   | Chromatography Column |   | Mixer 3 |   |
|--------------------|-----|---|-----------------------|---|---------|---|
| No. of Variables   |     |   |                       |   |         |   |
| Stream Variables   | 7   |   | 11                    |   | 12      |   |
| Chemical Reactions | 1   |   | 0                     |   | 0       |   |
| No. of Equations   |     |   |                       |   |         |   |
| Flows              |     | 0 |                       | 0 |         | 1 |
| Stream Composition |     | 1 |                       | 3 |         | 3 |
| System Performance |     | 1 |                       | 1 |         | 0 |
| Material Balances  |     | 4 |                       | 4 |         | 4 |
| Sum                | 8   | 6 | 11                    | 8 | 12      | 8 |
| DOF                | 2   |   | 3                     |   | 4       |   |



*You need a nomenclature sheet to define variables.*

## 5.6 Energy Balances

The heat duty for the coolers used during this process was calculated using Equation 5.7 below because no phase change occurred. In the absence of information on the specific heat capacity of HFCS, the value used for calculation was for corn syrup of 90 DE and 19.8 w/w% solids for E-101 and 79.4 for E-102, E-103, and E-104 as the closest specifications to the glucose syrup produced by this plant design. These values were selected closest to room temperature and were 0.889 Btu/lb°F and 0.583 Btu/lb°F (Critical Data Tables).

$$Q = \dot{m} * C_p * \Delta T \quad (5.7)$$

These values for E-101, E-102, and E-103 came out to be 6.4e6, 2.0e6, and 1.6e6 Btu/hr respectively.

The heat duty for the PBR was obtained using the overall heat transfer equation by combined conduction and convection in Equation 5.8. The heat duty value obtained was 34639 Btu/hr. Lastly, the heat duty for the evaporator and condenser were obtained using Equation 5.9 and 5.10 below, and the values obtained were 1.6e7 Btu/hr and 2.0e7 Btu/hr respectively.

$$Q = \frac{T_1 - T_4}{\frac{1}{h_i A_i} + \frac{r_o - r_i}{K_A A_{ALM}} + \frac{1}{h_o A_o}} \quad (5.8)$$

$$Q = UA\Delta T \quad (5.9)$$

$$Q = \dot{m}\lambda \quad (5.10)$$

## 5.7 Overall Material Balance with Process Streams

Material balances over each unit in the process were performed and is represented in Table 5.4 below. The component mass flow rates, as well as the stream temperature and pressure, are





represented as well as the total stream amount and this value is in units of pounds per hour (lbs/hr).

Table 5.4 Material Balance by Process Streams

| Stream Number                | 1      | 2      | 3      | 4      | 5      | 6       | 8       | 10      | 13      |
|------------------------------|--------|--------|--------|--------|--------|---------|---------|---------|---------|
| Temperature (°F)             | 77     | 77     | 77     | 77     | 221    | 203     | 221     | 140     | 140     |
| Pressure (psi)               | 14.7   | 14.7   | 14.7   | 10.7   | 17.5   | 14.7    | 14.7    | 10.7    | 10.7    |
| Component Mass Flow (lbs/hr) |        |        |        |        |        |         |         |         |         |
| Starch                       | 0      | 25,608 | 25,608 | 25,608 | 0      | 38,485  | 0       | 0       | 0       |
| Water                        | 18,700 | 3,201  | 71,102 | 71,102 | 48,778 | 106,855 | 58,311  | 58,311  | 58,310  |
| Waste Feed                   | 0      | 291    | 950    | 950    | 0      | 438     | 14,578  | 14,578  | 14,578  |
| Oligosaccharides             | 0      | 0      | 0      | 0      | 0      | 0       | 65,600  | 65,600  | 3,645   |
| Glucose                      | 0      | 0      | 0      | 0      | 0      | 0       | 7,289   | 7,289   | 69,245  |
| Fructose                     | 0      | 0      | 0      | 0      | 0      | 0       | 0       | 0       | 0       |
| TOTAL                        | 18,700 | 29,100 | 97,660 | 97,660 | 48,778 | 145,778 | 145,778 | 145,778 | 145,778 |

| Stream Number                | 14      | 15      | 17      | 18     | 20      | 21      | 22      | 24      | 27      |
|------------------------------|---------|---------|---------|--------|---------|---------|---------|---------|---------|
| Temperature (°F)             | 140     | 77      | 86      | 77     | 86      | 86      | 86      | 86      | 77      |
| Pressure (psi)               | 14.7    | 14.7    | 14.7    | 14.7   | 14.7    | 6       | 6       | 6       | 14.7    |
| Component Mass Flow (lbs/hr) |         |         |         |        |         |         |         |         |         |
| Starch                       | 0       | 0       | 0       | 0      | 0       | 0       | 0       | 0       | 0       |
| Water                        | 58,310  | 58,310  | 58,310  | 0      | 65,600  | 65,600  | 65,600  | 65,600  | 65,600  |
| Waste Feed                   | 14,578  | 14,578  | 14,578  | 14,578 | 0       | 0       | 0       | 0       | 0       |
| Oligosaccharides             | 3,645   | 3,645   | 3,645   | 0      | 3,280   | 3,280   | 3,280   | 3,280   | 3,280   |
| Glucose                      | 69,245  | 69,245  | 69,245  | 0      | 62,320  | 62,320  | 62,320  | 62,320  | 62,320  |
| Fructose                     | 0       | 0       | 0       | 0      | 0       | 0       | 0       | 0       | 0       |
| TOTAL                        | 145,778 | 145,778 | 145,778 | 14,578 | 131,200 | 131,200 | 131,200 | 131,200 | 131,200 |



| Stream Number                | 28             | 30            | 31            | 32            | 34            | 35            | 36            | 38            | 40            |
|------------------------------|----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Temperature (°F)             | 77             | 111           | 77            | 121           | 121           | 121           | 140           | 140           | 140           |
| Pressure (psi)               | 6              | 0.1           | 14.7          | 14.7          | 59            | 59            | 57            | 24            | 20            |
| Component Mass Flow (lbs/hr) |                |               |               |               |               |               |               |               |               |
| Starch                       | 0              | 0             | 0             | 0             | 0             | 0             | 0             | 0             | 0             |
| Water                        | 65,600         | 49,200        | 49,200        | 16400         | 16400         | 17,400        | 21,500        | 21,500        | 21,500        |
| Waste Feed                   | 0              | 0             | 0             | 0             | 0             | 0             | 0             | 0             | 0             |
| Oligosaccharides             | 3,280          | 0             | 0             | 3280          | 3280          | 3,300         | 1,900         | 1,900         | 1,900         |
| Glucose                      | 62,320         | 0             | 0             | 62320         | 62320         | 65,300        | 35,500        | 35,500        | 35,500        |
| Fructose                     | 0              | 0             | 0             | 0             | 0             | 0             | 27,100        | 27,100        | 27,100        |
| <b>TOTAL</b>                 | <b>131,200</b> | <b>49,200</b> | <b>49,200</b> | <b>82,000</b> | <b>82,000</b> | <b>86,000</b> | <b>86,000</b> | <b>86,000</b> | <b>86,000</b> |

| Stream Number                | 42            | 43            | 44           | 45           | 47            | 49            | 52            | 53            | 54           |
|------------------------------|---------------|---------------|--------------|--------------|---------------|---------------|---------------|---------------|--------------|
| Temperature (°F)             | 81            | 81            | 140          | 140          | 140           | 140           | 81            | 81            | 77           |
| Pressure (psi)               | 14.7          | 14.7          | 15.1         | 37           | 15.1          | 13            | 17.7          | 14.7          | 14.7         |
| Component Mass Flow (lbs/hr) |               |               |              |              |               |               |               |               |              |
| Starch                       | 0             | 0             | 0            | 0            | 0             | 0             | 0             | 0             | 0            |
| Water                        | 10,750        | 10,750        | 2,000        | 1,010        | 8,740         | 1,890         | 11,500        | 11,500        | 7,030        |
| Waste Feed                   | 0             | 0             | 0            | 0            | 0             | 0             | 0             | 0             | 0            |
| Oligosaccharides             | 967           | 967           | 180          | 0            | 790           | 640           | 1,000         | 1,000         | 0            |
| Glucose                      | 17,738        | 17,738        | 3,300        | 3,020        | 14,430        | 270           | 14,500        | 14,500        | 0            |
| Fructose                     | 13,545        | 13,545        | 2,520        | 0            | 11,040        | 8,200         | 19,000        | 19,000        | 0            |
| <b>TOTAL</b>                 | <b>43,000</b> | <b>43,000</b> | <b>8,000</b> | <b>4,030</b> | <b>35,000</b> | <b>11,000</b> | <b>46,000</b> | <b>46,000</b> | <b>7,030</b> |

## 6. ASPEN SIMULATION OF PROCESS

*This is for a bio process. Good job.*

Our plant design of HFCS was simulated using Aspen V9 Plus and our system converged with the truncated model, as shown in Figure 6.2. The property package used for our system was the UNIQUAC model. This determination was set through consideration of the HFCS process being primarily liquid phase and polar. The original design, shown in Figure 6.1, encompassed both major reactions, the hydrolysis of starch slurry, and the isomerization of glucose syrup. The starch feed could be substituted with cellulose as both are composed of glucose subunits (monomers). Recycle from the evaporator (EVAP) would be sent to the recycle stream that would originally be fed to the first mixer. With this configuration, there were notable unspecified values, particularly in the liquefaction and saccharification reactors. This is a result of limited kinetic data for this exergonic reaction, namely the kinetic factor information such as activation energy and k-constant values. For that reason, the truncated model shown in Figure 6.2, was made.

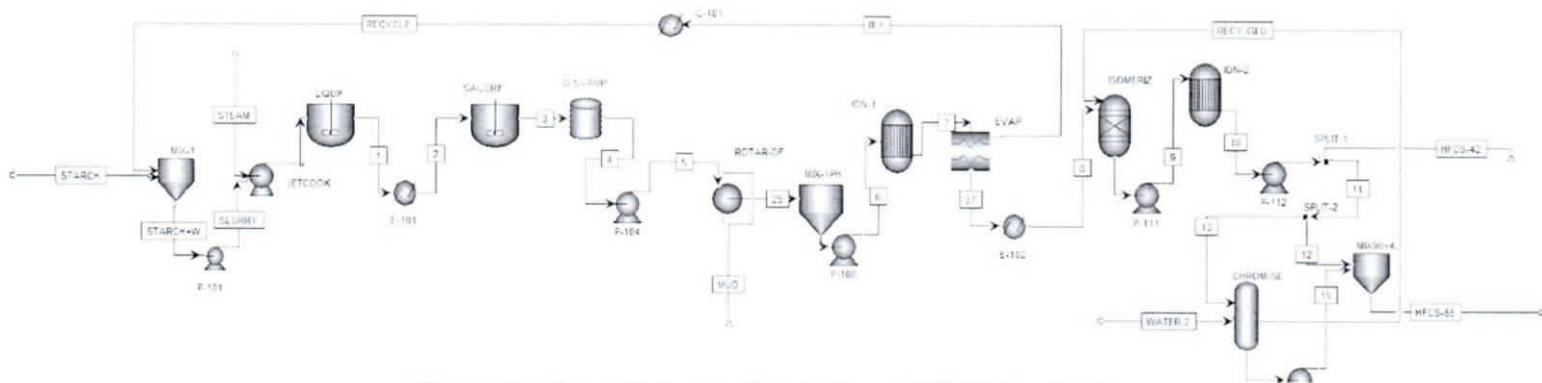


Figure 6.1 Overall Aspen Simulation of HFCS Production

The truncated model starts at the glucose holding tank, G-Syrup, omitting hydrolysis and slurry mixing. The mass balance of this glucose stream was initially set by values obtained from MEB calculations. Because the recycle stream from the evaporator enters the glucose tank as opposed to the initial slurry mixer, values of water in the glucose stream had to be normalized to



compensate for excess water in the loop. The isomerization reaction which is typically held in a packed bed reactor was to be initially modeled using a stoichiometric reactor with an equilibrium reaction scheme. Though for simplicity a yield reactor was used with an assumption of glucose yielding 42% fructose. The yield amount is described by the equilibrium reaction of glucose to fructose. There should be 50% of glucose converted with 100% reactor efficiency, but given the PBR for this reactor realistically has an efficiency of 85%, only 42.5 % can be converted.

Subsequent splitters, Split-1 and Split-2, have split fractions of 0.5. For liquid chromatography, a basic separator was used with a specification of the primary outlet stream being 90% fructose.

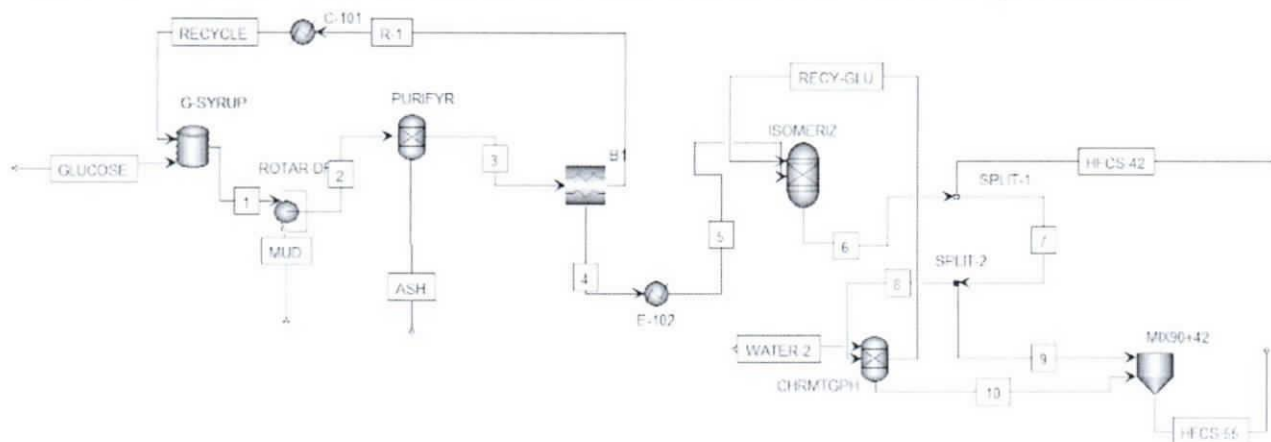


Figure 6.2 Truncated Aspen Simulation of HFCS Production

Our results for both products from the ASPEN simulation proved to be fairly close to our theoretical MEB calculations as shown in by data in Table 6.1 below.

Table 6.1 Simulation Results Comparison

|              | HFCS 42                     |                               | HFCS 55                     |                               |
|--------------|-----------------------------|-------------------------------|-----------------------------|-------------------------------|
|              | Simulated Mass Flow (lb/hr) | Theoretical Mass Flow (lb/hr) | Simulated Mass Flow (lb/hr) | Theoretical Mass Flow (lb/hr) |
| Fructose     | 13,738                      | 13,545                        | 19,555                      | 19,000                        |
| Glucose      | 18,263                      | 17,738                        | 16,005                      | 14,500                        |
| Water        | 10,733                      | 10,750                        | 10,741                      | 11,500                        |
| <b>TOTAL</b> | <b>42,734*</b>              | <b>43,000*</b>                | <b>46,302*</b>              | <b>46,000*</b>                |

\*Reflects total including oligosaccharide component not shown on table



## 7. CHEMICAL ENGINEERING DESIGN

### 7.1 Design of Major Equipment

#### R-101 and R-102

The first step in sizing the stirred tank reactor (STR) was determining the residence time. For the first hydrolysis step (liquefaction), a residence time of 2 hours was used as the basis of calculation (Buchholz 406). For saccharification, a residence time of 55 hours obtained from Figure 5.5 was used because it is in the range of residence time values given by Buchholz on page 407. *Alpha*-amylase Termamyl and Dextrozyme are the enzymes used for liquefaction and saccharification respectively (Whitehurst 215). After the residence time had been obtained, the total volume needed for liquefaction and saccharification was calculated using the relationship between residence time and volumetric flow rate as shown in Equation 7.1 below.

$$\text{Residence time } (\tau) = \frac{\text{volume } (v)}{\text{volumetric flow rate } (q)} \quad (7.1)$$

*for ts incorrect.*

The volume of the STR for liquefaction was calculated to be 1069 ft<sup>3</sup>. A much larger volume of 7063 ft<sup>3</sup> was obtained for saccharification. Data obtained from research verifies that this volume is appropriate for very large bio-reaction capacities (Humbird 4). Basic dimensions for each reactor were found using heuristics for STR design. These include a length to diameter ratio of 1.5 and an impeller diameter one-third of tank diameter (Brodkey 371). The height and diameter of the reactors were calculated using the formula for finding the volume of a cylinder also while considering heuristics given for vessels with elliptical bottoms. The volume of a cylinder with an elliptical bottom is obtained by the formula (cylinder volume + ( $\pi/24 * d^3$ )). Headspace allowance was factored by making the diameter equal to that of liquid height. The design of the vessel internals is just as important as sizing the volume of the vessel. The viscosity of the fluid being stirred plays a huge role in determining the agitator type that would be used for the reactor.





The viscosity of the fluid during hydrolysis is high with a value of about 1300cP during liquefaction and 600cP during saccharification. At these viscosities, a flat bade with a disk impeller would be appropriate. In addition to this, baffles were added because notable data shows that their addition aids efficient mixing in the reactor (Geankoplis 178). After selecting the impeller type, the power required (P) for agitation was calculated. Reynold's number was calculated using Equation 7.2 shown below.

$$N'_{Re} = \frac{\rho * N * D_a}{\mu} \quad (7.2)$$

Using Figure 7.1 below, a Reynold's number of 6.0e5 was plotted against curve 1 to get a power number (Np) for the liquefaction and saccharification phase (Geankoplis 181). With that power number, the power needed was calculated using Equation 7.3 below.

$$N_p = \frac{P}{\rho * N^3 * D_a^5} \quad (7.3)$$

Where: Da = agitator blade diameter, ft

N = agitator speed, revs/s

P = power

$\rho$  = density, lb/ft<sup>3</sup>

}  $\Rightarrow$  values?

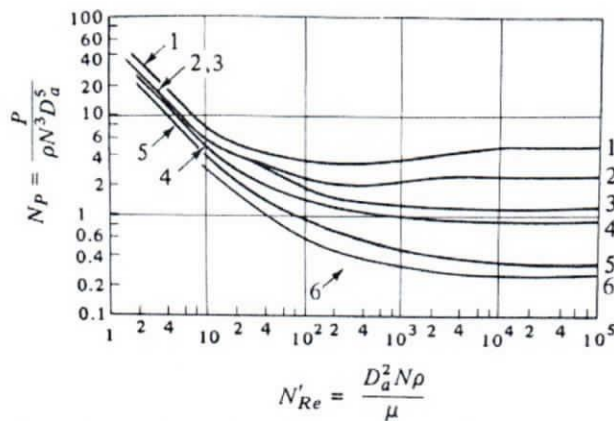


Figure 7.2-4 Power correlations for various impellers and baffles (see Fig. 7.2-3c for dimension  $D_a$ ,  $D_i$ ,  $J$ , and  $W$ ). Data from D. W. Dodge and A. B. Metzner. A.I.Ch.E. J., 5, 189, © 1959 American Institute of Chemical Engineers.

Curve 1. Flat six-blade turbine with disk (like Fig. 7.2-3 but six blades);  $D_a/W = 5$ ; four baffles each  $D_i/J = 12$ .

Curve 2. Flat six-blade open turbine (like Fig. 7.2-2c);  $D_a/W = 8$ ; four baffles each  $D_i/J = 12$ .

Curve 3. Six-blade open turbine (pitched-blade) but blades at  $45^\circ$  (like Fig. 7.2-2d);  $D_a/W = 8$ ; four baffles each  $D_i/J = 12$ .

Curve 4. Propeller (like Fig. 7.2-1); pitch =  $2D_a$ ; four baffles each  $D_i/J = 10$ ; also holds for same propeller in angular off-center position with no baffles.

Curve 5. Propeller; pitch =  $D_a$ ; four baffles each  $D_i/J = 10$ ; also holds for same propeller in angular off-center position with no baffles.

Curve 6. High-efficiency impeller; four baffles each  $D_i/J = 12$ .

Curves 1, 2, and 3 reprinted with permission from R. L. Bates, P. L. Fondy, and R. R. Corpstein, Ind. Eng. Chem. Proc. Des. Dev., 2, 310 (1963). Copyright by the American Chemical Society. Curves 4 and 5 from J. H. Rushton, E. W. Costich, and H. J. Everett, Chem. Eng. Progr., 46, 395, 467 (1950). With permission.

Figure 7.1 Graph for obtaining the power number used to calculate power requirement

### R-103

The design of a packed bed reactor is heavily influenced by the catalyst, which in turn depends on certain specifications such as shape, loading selection, dimensions, and life activity. Cylindrical catalysts will be used in this reactor because they usually have low voidage values (Afandizadeh 672). Low voidage facilitates an increase in surface area and the accommodation of more pellets. The loading selection that would be used is snowstorm filling, which involves passing the packing material over staggered wires or wire meshes. This method provides the

how low? range?



densest packing and gives the least voidage (Afandizadeh 676). In the design of packed beds, it is customary to assume that the particles are of equal size although this is far from reality. The catalyst used for this process has a diameter of 0.0098 ft and a length of 0.0082 ft. *No: days??* (Venkatasubramanian 144). Under the optimum operation conditions that have been described earlier, the typical half-life is in a range of 1800 - 1900 hours, and the enzyme can be used for about 3.5 half-lives (Antrim 135). With this type of activity, the enzyme can be used for 235 days before regeneration is needed.

To obtain the bed volume (working volume) for the packed bed reactor, the residence time equation from Equation 7.1 was used as the design equation. Under the given optimum operating conditions, a residence time of 4 hours is suitable (Venkatasubramanian 146). The volumetric flow rate was obtained using the density of glucose syrup and the mass inlet mass flow rate in Equation 7.4 below.

$$q = \frac{\text{mass flow rate (m)}}{\text{density (\rho)}} \quad \text{ok.} \quad (7.4)$$

At a range of 131°F – 140°F the density of glucose syrup is 11.73 lb/gallon. Using this information, the volumetric flow rate obtained was 980 ft<sup>3</sup>/hr. Using the volumetric flow rate obtained and the residence time, the working volume for the reactor is 3920 ft<sup>3</sup>. For this design, 14 reactors each with a working volume of 280 ft<sup>3</sup> ~~would be operated~~ in parallel (Buchholz 408). A typical industrial scale PBR has a diameter to height ratio of 0.3 and with this information, the height and diameter for one reactor were obtained to be 15.8 ft and 4.8 ft, respectively (Buchholz 408). It is important to note that the dimensions obtained above are for the reactor bed. The reactor vessel dimension was calculated with an additional 3ft added to the bed height. The additional space added would contain ceramic balls to promote uniform velocity across the bed

(Silla 392). The weight of catalyst in the bed for one reactor was calculated using Equation 7.5 below. The weight obtained for one reactor was 8450 lbs. The pressure drop across the reactor is 2 psi. It was found using Ergun's equation for an isothermal operation. The design equation used is Equation 7.6 below. Lastly, a heat duty of 34639 Btu/h was obtained using Equation 5.2 as described in section 5.5 above.

$$W = (1 - \phi)A_c Z * \rho_c \quad (7.5)$$

$$p = \frac{P}{P_o} = (1 - \alpha W)^{\frac{1}{2}} \quad (7.6)$$

$$\alpha = \frac{2\beta_o}{A_c(1-\phi)\rho_c P_o} \quad (lb^{-1}) \quad (7.7)$$

$$\beta_o = \frac{G(1-\phi)}{\rho_o g_c D_p \phi^3} * \left[ \frac{150(1-\phi)\mu}{D_p} + 1.75G \right] * \frac{14.7}{12} \quad (psi) \quad (7.8)$$

$$G \text{ (superficial mass velocity)} = \rho_o u \quad \left( \frac{lb}{ft^2 \cdot h} \right) \quad (7.9)$$

Where:

$\Phi$  = void fraction

$D_p$  = diameter of the particle in the bed, (ft)

$\mu$  = viscosity of liquid passing through the bed, lb/ft<sup>2</sup>·h

$\rho_o$  = liquid density, lb/ft<sup>3</sup>

$\rho_c$  = catalyst density, lb/ft<sup>3</sup>

$g_c = 32.174 \text{ lb} \cdot \text{ft} / \text{s}^2 \cdot \text{lb}_f$  (conversion factor)

$A_c$  = cross-sectional area of bed

place in  
nomenclature  
section





$Z$  = Bed height

$P_o$  = inlet pressure

$u$  = superficial velocity = volumetric flow rate  $\div$  cross-sectional area

### CC-101

A simulated moving bed is applied in this design to allow for continuous countercurrent chromatographic separation of the glucose-fructose syrup mixture (Schulte 3). The most common configuration of this method involves arranging about twelve fixed bed chromatography columns in series with two inlet and two outlet streams. The inlet streams being the incoming syrup to be separated and the eluant which is water and the outlet streams being the enriched syrup stream as the extract and the recycled glucose stream as the raffinate. The inlet and outlet ports are shifted one single column ahead in the direction of the fluid flow after the established switching period and this allows for the simulation of continuous flow (Azevedo 171). A separation cycle is completed when the initial location of the input and output ports have been reached.

In the design of the single fixed bed chromatography column, a laboratory experiment was scaled up to obtain the dimensions of the columns used in this design (Wang 545). The laboratory column had a length of 0.98 ft and an internal diameter of 0.049 ft. The retention times of glucose and fructose obtained from the chromatogram were 10.5 and 8.8 minutes respectively and this was used in Equation 7.10 to find the average theoretical number of plates for the analytical column to be 2057.

$$\text{Theoretical Number of Plates (N)} = 16 * \left( \frac{\text{retention time (t}_r\text{)}}{\text{baseline peak width (w)}} \right)^2 \quad (7.10)$$



This value was then used in Equation 7.11 to calculate the height equivalent of a theoretical plate (HETP) to be 0.00048 ft.

$$\text{HETP} = \frac{\text{column length (L)}}{N} \quad (7.11)$$

Peak resolution gives the degree of separation of two components in a mixture (Chromatographic Methods). This was calculated using Equation 7.12 below to give a peak resolution of 1.71.

$$\text{Resolution (R)} = \frac{2(t_{ra} - t_{rb})}{w_a + w_b} \quad (7.12)$$

For this design a peak resolution of 3.5 was used to achieve better component separation (Theory of HPLC) and using Equation 7.10, the theoretical number of plates for this column's design was calculated to be 11255.

$$R = \frac{1}{4} * \sqrt{N} * \frac{(\alpha - 1)}{(\alpha)} * \frac{(k)}{(1+k)} \quad (7.13)$$

Where  $\alpha$  and  $k$  are component selectivity and retention factors respectively. These values are independent of column length and do not change with it (Chromatographic Methods), therefore, the number of theoretical plates of a different column can be calculated using:

$$\frac{R_1}{R_2} = \frac{\sqrt{N_1}}{\sqrt{N_2}} \quad (7.14)$$

The packed column length for this design was then calculated using Equation 7.11 and the height equivalent of a theoretical plate of 0.00048 ft and this came to be 4.13 ft.

The packing used for this design was the Dowex Monoshpere 99 in the  $\text{Ca}^{2+}$  form which is a gel-type resin with a particle size of 320 microns and is used in HFCS enrichment. In calculating the total column length, freeboard accounting for 70% backwash expansion of the resin was added with an additional 2 ft for the safety factor (DOW). This brought the total



column length to 9 ft. The column diameter was calculated using a recommended length to diameter ratio of 3 for ion exchange columns (Desal Supplies) and this gave a value of 3 ft.

The column switching time can be calculated using Equation 7.15

$$t^* = \frac{L_c}{u_s} \quad (7.15)$$

With a solid velocity ( $u_s$ ) of 0.0019 ft/sec and a column length ( $L_c$ ) of 9 feet, the switching time ( $t^*$ ) was calculated to be 78 minutes.

#### M-103

*what is the phase in this mixer?*

The volume of the mixer was determined using Equation 7.1. With a residence time of 10 minutes, the volume obtained was 36 ft<sup>3</sup>. To determine the amount of power needed to agitate the mixer, Equation 7.3 was used. The power (kW) for mixers 101, 102, and 103 are 2.7, 0.04, and 0.32 respectively. The density varied between 30% or 50% of the dry substance of the slurry. The agitator speed was set to 0.832 revolutions per second (Lele 1). The agitator diameter was based on the diameter of the mixing tank. The dimensionless power number was set to 0.28 for gate paddle agitators (Lele 1). The volumes of the mixers 101 through 103 are 758, 186, and 36 ft<sup>3</sup> respectively. The residence times between 5 – 10 minutes were used for each mixer (Perry 11). To determine the diameter of the mixer, Equation 7.16 was used.

$$V = \frac{\pi}{4} * d^2 * h \quad (7.16)$$

Where,

V = volume of the cylinder (ft<sup>3</sup>)

d = diameter of the cylinder (ft)

$h$  = height of cylinder (ft)

The diameters for mixers 101 through 103 are 8, 4, and 3 ft, respectively. The height of mixers 101 through 103 are 14, 18, and 6 ft, respectively. The construction material recommended is stainless steel 316 and the type of agitator is gate paddles (Walas 287).

## **7.2 Equipment Listing and Specifications**

The specification sheets for the major units and equipment involved in the overall process are shown subsequently. The cost values shown are for the total number of units required including spares and backups and the design data is per vessel.



| M-101                                                                       |                      |                                  |                   |          |
|-----------------------------------------------------------------------------|----------------------|----------------------------------|-------------------|----------|
| <b>Identification</b>                                                       | Item:                | Mixer                            |                   |          |
|                                                                             | Item No:             | 1                                | Date:             | 05/05/20 |
|                                                                             | No. Required:        | 1                                |                   |          |
|                                                                             | Total Purchase Cost: | \$15,290                         | Bare Module Cost: | \$38,225 |
| <b>Function:</b> Mixing of starch powder and water to produce starch slurry |                      |                                  |                   |          |
| <b>Operation:</b> Batch process                                             |                      |                                  |                   |          |
|                                                                             |                      |                                  |                   |          |
|                                                                             | <b>Feed</b>          | <b>Product</b>                   |                   |          |
| <b>Materials Handled:</b>                                                   |                      |                                  |                   |          |
| Total Flow (lb/hr):                                                         | 29,100               | 97,660                           |                   |          |
| Volumetric Flow (U.S. gallons/hr):                                          | 3,092                | 10,307                           |                   |          |
| <b>Component Flow (lb/hr):</b>                                              |                      |                                  |                   |          |
| Starch                                                                      | 25,608               | 25,608                           |                   |          |
| Water                                                                       | 71,101               | 71,102                           |                   |          |
| Waste Feed                                                                  | 291                  | 950                              |                   |          |
| <b>Operating Conditions:</b>                                                |                      |                                  |                   |          |
| Normal Operating Temp. (°F):                                                | 77                   | Normal Operating Pressure (psi): | 14.7              |          |
| Max. Design Temp. (°F):                                                     | 127                  | Max. Design Pressure (psi):      | 150               |          |
| Min. Design Temp. (°F):                                                     | 52                   | Design Pressure (psi):           | 38.7              |          |
| Residence Time (mins):                                                      | 5-10                 |                                  |                   |          |
| <b>Design Data:</b>                                                         |                      |                                  |                   |          |
| Height (ft):                                                                | 14                   | Material:                        | SS 316            |          |
| Diameter (ft):                                                              | 8                    | Type of agitator:                | Gate Paddles      |          |
| Volume (ft³):                                                               | 758                  | Diameter of agitator (ft):       | 7                 |          |
| Power Consumed (kW):                                                        | 2.7                  | No. of impellers:                | 1                 |          |
|                                                                             |                      | Orientation:                     | Vertical          |          |
| <b>Comments:</b>                                                            | Open mixer vessel    |                                  |                   |          |

| P-101                                                                    |                      |                             |                   |          |
|--------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                    | Item:                | Progressive Cavity Pump     |                   |          |
|                                                                          | Item No:             | 1                           | Date:             | 05/05/20 |
|                                                                          | No. Required:        | 2                           |                   |          |
|                                                                          | Total Purchase Cost: | \$8,970                     | Bare Module Cost: | \$29,601 |
| <b>Function:</b> Transportation of starch slurry to STR for liquefaction |                      |                             |                   |          |
| <b>Operation:</b> Batch process                                          |                      |                             |                   |          |
|                                                                          |                      |                             |                   |          |
|                                                                          | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                |                      |                             |                   |          |
| Total Flow (lb/hr):                                                      | 97,600               | 97,600                      |                   |          |
| Volumetric Flow (U.S. gallons/hr):                                       | 10,307               | 10,307                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                           |                      |                             |                   |          |
| Starch                                                                   | 25,608               | 25,608                      |                   |          |
| Water                                                                    | 71,102               | 71,102                      |                   |          |
| Waste Feed                                                               | 950                  | 950                         |                   |          |
| <b>Operating Conditions:</b>                                             |                      |                             |                   |          |
| Phase                                                                    | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                      |                      |                             |                   |          |
| NPSH (ft):                                                               | 9.84                 | Material:                   | SS 316            |          |
| Hydraulic Power (hp):                                                    | 0.41                 | Allowable $\Delta P$ (psi): | 4.04              |          |
| Brake Power (hp):                                                        | 0.58                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                                | 0.44                 | Head (ft):                  | 8                 |          |





| JC-101                                                                                               |                           |                |                   |          |
|------------------------------------------------------------------------------------------------------|---------------------------|----------------|-------------------|----------|
| <b>Identification</b>                                                                                | Item:                     | Jet Cooker     |                   |          |
|                                                                                                      | Item No:                  | 1              | Date:             | 05/05/20 |
|                                                                                                      | No. Required:             | 1              |                   |          |
|                                                                                                      | Total Purchase Cost:      | \$454          | Bare Module Cost: | \$1,816  |
| <b>Function:</b> Applying steam to heat starch slurry to optimum temperature for liquefaction in STR |                           |                |                   |          |
| <b>Operation:</b> Batch process                                                                      |                           |                |                   |          |
|                                                                                                      |                           |                |                   |          |
|                                                                                                      | <b>Feed</b>               | <b>Product</b> | <b>Steam</b>      |          |
| <b>Materials Handled:</b>                                                                            |                           |                |                   |          |
| Total Flow (lb/hr):                                                                                  | 97,660                    | 145,778        | 48,778            |          |
| Volumetric Flow (U.S. gallons/hr):                                                                   | 40,822                    | 61,355         | 7,017             |          |
| <b>Component Flow (lb/hr):</b>                                                                       |                           |                |                   |          |
| Starch                                                                                               | 25,608                    | 38,485         | -                 |          |
| Water                                                                                                | 71,102                    | 106,855        | 48,778            |          |
| Waste feed                                                                                           | 950                       | 438            | -                 |          |
| <b>Operating Conditions:</b>                                                                         |                           |                |                   |          |
| Phase                                                                                                | Liquid                    | Liquid         | Vapor             |          |
| Operating Temperature (°F):                                                                          | 105                       | 203            | 221               |          |
| Operating Pressure (psi)                                                                             | 14.7                      | 14.7           | 17.5              |          |
| <b>Design Data:</b>                                                                                  |                           |                |                   |          |
| Material:                                                                                            | SS 316                    |                |                   |          |
| Orientation:                                                                                         | Horizontal                |                |                   |          |
| <b>Comments:</b>                                                                                     | Steam injection operation |                |                   |          |

| R-101                                        |                      |                                             |                   |             |
|----------------------------------------------|----------------------|---------------------------------------------|-------------------|-------------|
| <b>Identification</b>                        | Item:                | Stirred Tank Reactor                        |                   |             |
|                                              | Item No:             | 1                                           | Date:             | 05/05/20    |
|                                              | No Required:         | 7                                           |                   |             |
|                                              | Total Purchase Cost: | \$525,000                                   | Bare Module Cost: | \$1,575,000 |
| <b>Function:</b> Liquefaction of corn starch |                      |                                             |                   |             |
| <b>Operation:</b> Batch process              |                      |                                             |                   |             |
|                                              | <b>Feed</b>          | <b>Product</b>                              |                   |             |
| <b>Materials Handled:</b>                    |                      |                                             |                   |             |
| Total Flow (lb/hr):                          | 145,778              | 145,778                                     |                   |             |
| Volumetric Flow (U.S. gallons/hr):           | 15,485               | 15,485                                      |                   |             |
| <b>Component Flow (lb/hr):</b>               |                      |                                             |                   |             |
| Starch                                       | 38,485               | -                                           |                   |             |
| Glucose                                      | -                    | 7,289                                       |                   |             |
| Oligosaccharides                             | -                    | 65,600                                      |                   |             |
| Water                                        | 106,855              | 58,311                                      |                   |             |
| Waste Feed                                   | 438                  | 14,578                                      |                   |             |
| <b>Operating Conditions:</b>                 |                      |                                             |                   |             |
| Phase                                        | Liquid               | Liquid                                      |                   |             |
| Temperature (°F)                             | 221                  | 221                                         |                   |             |
| Pressure (psi)                               | 14.7                 | 14.7                                        |                   |             |
| Residence Time (hours)                       | 2                    |                                             |                   |             |
| <b>Design Data:</b>                          |                      |                                             |                   |             |
| <b>Vessel</b>                                |                      | <b>Vessel Internals</b>                     |                   |             |
| Volume (ft <sup>3</sup> )                    | 1,069                | Agitator Type                               | Flat blade        |             |
| Height (ft)                                  | 14.5                 | Impeller Type                               | Disk              |             |
| Diameter (ft)                                | 9.68                 | No. of Impellers                            | 3                 |             |
| Skirt Height (ft)                            | 2.9                  | Impeller Diameter (ft)                      | 3.23              |             |
| Liquid Height (ft)                           | 9.68                 | Impeller Disk Diameter (ft)                 | 2.42              |             |
| Material                                     | SS 316               | Impeller Speed (rpm)                        | 97.08             |             |
|                                              |                      | Power Requirement (kW)                      | 21.40             |             |
|                                              |                      | No. of Blades                               | 6                 |             |
|                                              |                      | Blade Length (ft)                           | 0.81              |             |
|                                              |                      | Blade Width (ft)                            | 0.65              |             |
|                                              |                      | Baffle Width (ft)                           | 0.97              |             |
|                                              |                      | Baffle tip distance from vessel bottom (ft) | 1.936             |             |
| <b>Comments:</b>                             | 7 reactors in series |                                             |                   |             |



| P-102                                                                        |                      |                             |                   |           |
|------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|-----------|
| <b>Identification</b>                                                        | Item:                | Progressive Cavity Pump     |                   |           |
|                                                                              | Item No:             | 2                           | Date:             | 05/05/20  |
|                                                                              | No. Required:        | 2                           |                   |           |
|                                                                              | Total Purchase Cost: | \$214,058                   | Bare Module Cost: | \$706,391 |
| <b>Function:</b> Transportation of starch slurry to STR for saccharification |                      |                             |                   |           |
| <b>Operation:</b> Batch process                                              |                      |                             |                   |           |
|                                                                              | <b>Feed</b>          | <b>Product</b>              |                   |           |
| <b>Materials Handled:</b>                                                    |                      |                             |                   |           |
| Total Flow (lb/hr):                                                          | 145,778              | 145,778                     |                   |           |
| Volumetric Flow (U.S. gallons/hr):                                           | 15,485               | 15,485                      |                   |           |
| <b>Component Flow (lb/hr):</b>                                               |                      |                             |                   |           |
| Glucose                                                                      | 7,289                | 7,289                       |                   |           |
| Oligosaccharides                                                             | 65,600               | 65,600                      |                   |           |
| Water                                                                        | 58,311               | 58,311                      |                   |           |
| Waste Feed                                                                   | 14,578               | 14,578                      |                   |           |
| <b>Operating Conditions:</b>                                                 |                      |                             |                   |           |
| Phase                                                                        | Liquid               | Liquid                      |                   |           |
| <b>Design Data:</b>                                                          |                      |                             |                   |           |
| NPSH (ft):                                                                   | 9.84                 | Material:                   | SS 316            |           |
| Hydraulic Power (hp):                                                        | 5.32                 | Allowable $\Delta P$ (psi): | 17.82             |           |
| Brake Power (hp):                                                            | 8.18                 | Efficiency (%):             | 65                |           |
| Shaft work required (kW):                                                    | 6.0                  | Head (ft):                  | 72                |           |

| E-101                                                       |                      |                                  |                      |           |
|-------------------------------------------------------------|----------------------|----------------------------------|----------------------|-----------|
| <b>Identification</b>                                       | Item:                | Shell and Tube Heat Exchanger    |                      |           |
|                                                             | Item No:             | 1                                | Date:                | 05/05/20  |
|                                                             | No. Required:        | 2                                |                      |           |
|                                                             | Total Purchase Cost: | \$47,348                         | Bare Module Cost:    | \$150,093 |
| <b>Function:</b> Cooling starch slurry for saccharification |                      |                                  |                      |           |
| <b>Operation:</b> Batch process                             |                      |                                  |                      |           |
|                                                             | <b>Tube Side</b>     | <b>Shell Side</b>                |                      |           |
| <b>Materials Handled:</b>                                   |                      |                                  |                      |           |
| Total Flow (lb/hr):                                         | 145,778              | 145,778                          |                      |           |
| Volumetric Flow (U.S. gallons/hr):                          | 15,485               | 15,485                           |                      |           |
| <b>Component Flow (lb/hr):</b>                              |                      |                                  |                      |           |
| Glucose                                                     | 7,289                | 7,289                            |                      |           |
| Oligosaccharides                                            | 65,600               | 65,600                           |                      |           |
| Water                                                       | 58,311               | 58,311                           |                      |           |
| Waste Feed                                                  | 14,578               | 14,578                           |                      |           |
| <b>Operating Conditions:</b>                                |                      |                                  |                      |           |
| Normal Operating Temp. (°F):                                | 68-221               | Normal Operating Pressure (psi): | 14.7                 |           |
| Max. Operating Temp. (°F):                                  | 271                  | Max. Operating Pressure (psi):   | 40                   |           |
| Min. Operating Temp. (°F):                                  | 43                   | Design Operating Pressure (psi): | 65                   |           |
| <b>Design Data:</b>                                         |                      |                                  |                      |           |
| Heat Transfer Area (ft <sup>2</sup> ):                      | 381                  | Material:                        | SS 316               |           |
| $\Delta T_{LM}$ (°F):                                       | 104                  | Shell Diameter(in):              | 24                   |           |
| Shell-Tube Arrangement:                                     | 2-4                  | Tube Outside Diameter(in):       | 0.75 on 1" Triangles |           |
| Heat required (kW):                                         | 1,760                | Tube Count:                      | 428                  |           |
| Overall Heat Transfer Coef. (BTU/hr-ft <sup>2</sup> -R):    | 150                  | TEMA Config.:                    | AEL                  |           |



| R-102                                                        |                       |                                             |                   |              |
|--------------------------------------------------------------|-----------------------|---------------------------------------------|-------------------|--------------|
| <b>Identification</b>                                        | Item:                 | Stirred Tank Reactor                        |                   |              |
|                                                              | Item No:              | 2                                           | Date:             | 05/05/20     |
|                                                              | No Required:          | 29                                          |                   |              |
|                                                              | Total Purchase Cost:  | \$11,600,000                                | Bare Module Cost: | \$34,800,000 |
| <b>Function:</b> Saccharification of corn starch to dextrose |                       |                                             |                   |              |
| <b>Operation:</b> Batch process                              |                       |                                             |                   |              |
|                                                              | <b>Feed</b>           | <b>Product</b>                              |                   |              |
| <b>Materials Handled:</b>                                    |                       |                                             |                   |              |
| Total Flow (lb/hr):                                          | 145,778               | 145,778                                     |                   |              |
| Volumetric Flow (U.S. gallons/hr):                           | 15,485                | 15,485                                      |                   |              |
| <b>Component Flow (lb/hr):</b>                               |                       |                                             |                   |              |
| Glucose                                                      | 7,289                 | 69,245                                      |                   |              |
| Oligosaccharides                                             | 65,600                | 3,645                                       |                   |              |
| Water                                                        | 58,311                | 58,310                                      |                   |              |
| Waste feed                                                   | 14,578                | 14,578                                      |                   |              |
| <b>Operating Conditions:</b>                                 |                       |                                             |                   |              |
| Phase                                                        | Liquid                | Liquid                                      |                   |              |
| Temperature (°F)                                             | 140                   | 140                                         |                   |              |
| Pressure (psi)                                               | 10.7                  | 10.7                                        |                   |              |
| Residence Time (hours)                                       | 55                    |                                             |                   |              |
| <b>Design Data:</b>                                          |                       |                                             |                   |              |
| <b>Vessel</b>                                                |                       | <b>Vessel Internals</b>                     |                   |              |
| Volume (ft <sup>3</sup> )                                    | 7,063                 | Agitator Type                               | Flat-blade        |              |
| Height (ft)                                                  | 27.3                  | Impeller Type                               | Disk              |              |
| Diameter (ft)                                                | 18.2                  | No. of Impellers                            | 3                 |              |
| Skirt Height (ft)                                            | 5.46                  | Impeller Diameter (ft)                      | 6.07              |              |
| Liquid Height (ft)                                           | 18.2                  | Impeller Disk Diameter (ft)                 | 4.55              |              |
| Material                                                     | SS 316                | Impeller Speed (rpm)                        | 51.63             |              |
|                                                              |                       | Power Requirement (kW)                      | 21.40             |              |
|                                                              |                       | No. of Blades                               | 6                 |              |
|                                                              |                       | Blade Length (ft)                           | 1.52              |              |
|                                                              |                       | Blade Width (ft)                            | 1.21              |              |
|                                                              |                       | Baffle Width (ft)                           | 1.82              |              |
|                                                              |                       | Baffle tip distance from vessel bottom (ft) | 3.64              |              |
| <b>Comments:</b>                                             | 29 reactors in series |                                             |                   |              |

| P-103                                                                  |                      |                             |                   |          |
|------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                  | Item:                | Centrifugal Pump            |                   |          |
|                                                                        | Item No:             | 3                           | Date:             | 05/05/20 |
|                                                                        | No. Required:        | 2                           |                   |          |
|                                                                        | Total Purchase Cost: | \$4,165                     | Bare Module Cost: | \$13,745 |
| <b>Function:</b> Transportation of glucose syrup to glucose syrup tank |                      |                             |                   |          |
| <b>Operation:</b> Batch process                                        |                      |                             |                   |          |
|                                                                        | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                              |                      |                             |                   |          |
| Total Flow (lb/hr)                                                     | 145,778              | 145,778                     |                   |          |
| Volumetric Flow (U.S. Gallons/hr)                                      | 15,485               | 15,485                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                         |                      |                             |                   |          |
| Glucose                                                                | 69,245               | 69,245                      |                   |          |
| Oligosaccharides                                                       | 3,645                | 3,645                       |                   |          |
| Water                                                                  | 58,310               | 58,310                      |                   |          |
| Waste Feed                                                             | 14,578               | 14,578                      |                   |          |
| <b>Operating Conditions:</b>                                           |                      |                             |                   |          |
| Phase:                                                                 | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                    |                      |                             |                   |          |
| NPSH (ft):                                                             | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                  | 0.79                 | Allowable $\Delta P$ (psi): | 8.73              |          |
| Brake Power (hp):                                                      | 1.13                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                              | 0.52                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                         | 3450                 | Head (ft):                  | 11                |          |





| E-102                                                      |                      |                                  |                      |           |
|------------------------------------------------------------|----------------------|----------------------------------|----------------------|-----------|
| <b>Identification</b>                                      | Item:                | Shell and Tube Heat Exchanger    |                      |           |
|                                                            | Item No:             | 2                                | Date:                | 05/05/20  |
|                                                            | No. Required:        | 2                                |                      |           |
|                                                            | Total Purchase Cost: | \$47,348                         | Bare Module Cost:    | \$150,093 |
| <b>Function:</b> Cooling glucose syrup for storage in tank |                      |                                  |                      |           |
| <b>Operation:</b> Batch process                            |                      |                                  |                      |           |
|                                                            | <b>Tube Side</b>     | <b>Shell Side</b>                |                      |           |
| <b>Materials Handled:</b>                                  |                      |                                  |                      |           |
| Total Flow (lb/hr):                                        | 145,778              | 145,778                          |                      |           |
| Volumetric Flow (U.S. gallons/hr):                         | 15,485               | 15,485                           |                      |           |
| <b>Component Flow(lb/hr):</b>                              |                      |                                  |                      |           |
| Starch                                                     | 69,245               | 69,245                           |                      |           |
| Oligosaccharides                                           | 3,645                | 3,645                            |                      |           |
| Water                                                      | 58,310               | 58,310                           |                      |           |
| Waste Feed                                                 | 14,578               | 14,578                           |                      |           |
| <b>Operating Conditions:</b>                               |                      |                                  |                      |           |
| Normal Operating Temp. (°F):                               | 68-221               | Normal Operating Pressure (psi): | 14.7                 |           |
| Max. Operating Temp. (°F):                                 | 271                  | Max. Operating Pressure (psi):   | 40                   |           |
| Min. Operating Temp. (°F):                                 | 43                   | Design Operating Pressure (psi): | 65                   |           |
| <b>Design Data:</b>                                        |                      |                                  |                      |           |
| Heat Transfer Area (ft <sup>2</sup> ):                     | 381                  | Material:                        | SS 316               |           |
| $\Delta T_{LM}$ (°F):                                      | 104                  | Shell Diameter(in):              | 24                   |           |
| Shell-Tube Arrangement:                                    | 2-4                  | Tube Outside Diameter(in):       | 0.75 on 1" Triangles |           |
| Heat required (kW):                                        | 1,760                | Tube Count:                      | 428                  |           |
| Overall Heat Transfer Coef. (BTU/hr-ft <sup>2</sup> -R):   | 150                  | TEMA Config.:                    | AEL                  |           |

| TK-101                                                                        |                      |                                  |                   |          |
|-------------------------------------------------------------------------------|----------------------|----------------------------------|-------------------|----------|
| <b>Identification</b>                                                         | Item:                | Tank                             |                   |          |
|                                                                               | Item No:             | 1                                | Date:             | 05/05/20 |
|                                                                               | No. Required:        | 1                                |                   |          |
|                                                                               | Total Purchase Cost: | \$5,300                          | Bare Module Cost: | \$15,900 |
| <b>Function:</b> Holding tank for glucose syrup before entering rotary filter |                      |                                  |                   |          |
| <b>Operation:</b> Batch process                                               |                      |                                  |                   |          |
|                                                                               | <b>Feed</b>          | <b>Product</b>                   |                   |          |
| <b>Materials Handled:</b>                                                     |                      |                                  |                   |          |
| Total Flow (lb/hr):                                                           | 145,778              | 145,778                          |                   |          |
| Volumetric Flow (U.S. gallons/hr):                                            | 15,485               | 15,485                           |                   |          |
| <b>Component Flow (lb/hr):</b>                                                |                      |                                  |                   |          |
| Glucose                                                                       | 69,245               | 69,245                           |                   |          |
| Oligosaccharides                                                              | 3,645                | 3,645                            |                   |          |
| Water                                                                         | 58,310               | 58,310                           |                   |          |
| Waste Feed                                                                    | 14,578               | 14,578                           |                   |          |
| <b>Operating Conditions:</b>                                                  |                      |                                  |                   |          |
| Phase                                                                         | Liquid               | Liquid                           |                   |          |
| Normal Operating Temperature (°F):                                            | 77                   | Normal Operating Pressure (psi): | 14                |          |
| Max. Operating Temperature (°F):                                              | 127                  | Max. Operating Pressure (psi):   | 150               |          |
| Min. Operating Temperature (°F):                                              | 52                   | Design Operating Pressure (psi): | 30                |          |
| <b>Design Data:</b>                                                           |                      |                                  |                   |          |
| Orientation:                                                                  | Vertical             | Material:                        | SS 316            |          |
| Height (ft):                                                                  | 16                   | Type:                            | Conical Roof      |          |
| Diameter (ft):                                                                | 9                    | Volume (ft³):                    | 1240              |          |



| P -104                                                            |                      |                             |                   |          |
|-------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                             | Item:                | Centrifugal Pump            |                   |          |
|                                                                   | Item No:             | 4                           | Date:             | 05/05/20 |
|                                                                   | No. Required:        | 2                           |                   |          |
|                                                                   | Total Purchase Cost: | \$5,286                     | Bare Module Cost: | \$17,444 |
| <b>Function:</b> Transportation of glucose syrup to rotary filter |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                              |                      |                             |                   |          |
|                                                                   | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                         |                      |                             |                   |          |
| Total Flow (lb/hr)                                                | 145,778              | 145,778                     |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                 | 15,485               | 15,485                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                    |                      |                             |                   |          |
| Glucose                                                           | 69,245               | 69,245                      |                   |          |
| Oligosaccharides                                                  | 3,645                | 3,645                       |                   |          |
| Water                                                             | 58,310               | 58,310                      |                   |          |
| Waste Feed                                                        | 14,578               | 14,578                      |                   |          |
| <b>Operating Conditions:</b>                                      |                      |                             |                   |          |
| Phase                                                             | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                               |                      |                             |                   |          |
| NPSH (ft):                                                        | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                             | 0.60                 | Allowable $\Delta P$ (psi): | 2.01              |          |
| Brake Power (hp):                                                 | 0.86                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                         | 0.18                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                    | 3450                 | Head (ft):                  | 8                 |          |



| F-101                                                        |                      |                |                   |           |
|--------------------------------------------------------------|----------------------|----------------|-------------------|-----------|
| <b>Identification</b>                                        | Item:                | Rotary Filter  |                   |           |
|                                                              | Item No:             | 1              | Date:             | 05/05/20  |
|                                                              | No Required:         | 1              |                   |           |
|                                                              | Total Purchase Cost: | \$252,252      | Bare Module Cost: | \$908,107 |
| <b>Function:</b> Separation of impurities from glucose syrup |                      |                |                   |           |
| <b>Operation:</b> Continuous process                         |                      |                |                   |           |
|                                                              | <b>Feed</b>          | <b>Product</b> |                   |           |
| <b>Materials Handled:</b>                                    |                      |                |                   |           |
| Total Flow (lb/hr):                                          | 145,778              | 131,200        |                   |           |
| Volumetric Flow (U.S. gallons/hr):                           | 15,485               | 11,184         |                   |           |
| <b>Component Flow (lb/hr):</b>                               |                      |                |                   |           |
| Glucose                                                      | 69,245               | 62,320         |                   |           |
| Oligosaccharides                                             | 3,645                | 3,280          |                   |           |
| Water                                                        | 58,310               | 65,600         |                   |           |
| Waste Feed                                                   | 14,578               | -              |                   |           |
| <b>Operating Conditions:</b>                                 |                      |                |                   |           |
| Phase                                                        | Liquid               | Liquid         |                   |           |
| Temperature (°F)                                             | 86                   | 86             |                   |           |
| Pressure (psi)                                               | 14.7                 | 14.7           |                   |           |
| <b>Design Data:</b>                                          |                      |                |                   |           |
| <b>Vessel</b>                                                |                      |                |                   |           |
| Orientation                                                  | Horizontal drum      |                |                   |           |
| Drum Diameter (ft)                                           | 7                    |                |                   |           |
| Drum Length (ft)                                             | 10                   |                |                   |           |
| Rotating Speed (rpm)                                         | 2                    |                |                   |           |
| Precoat Discharge                                            | Diatomaceous earth   |                |                   |           |
| Capacity (lb/hr*ft <sup>2</sup> )                            | 200                  |                |                   |           |
| Surface area of filtration (ft <sup>2</sup> )                | 729                  |                |                   |           |
| Material                                                     | SS 304L              |                |                   |           |





| P-105                                                                                    |                      |                             |                   |          |
|------------------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                                    | Item:                | Centrifugal Pump            |                   |          |
|                                                                                          | Item No:             | 5                           | Date:             | 05/05/20 |
|                                                                                          | No. Required:        | 2                           |                   |          |
|                                                                                          | Total Purchase Cost: | \$13,882                    | Bare Module Cost: | \$45,811 |
| <b>Function:</b> Transportation of glucose syrup from rotary filter to adsorption column |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                                     |                      |                             |                   |          |
|                                                                                          | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                                |                      |                             |                   |          |
| Total Flow (lb/hr)                                                                       | 131,200              | 131,200                     |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                                        | 11,184               | 11,184                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                                           |                      |                             |                   |          |
| Glucose                                                                                  | 62,320               | 62,320                      |                   |          |
| Oligosaccharides                                                                         | 3,280                | 3,280                       |                   |          |
| Water                                                                                    | 65,600               | 65,600                      |                   |          |
| <b>Operating Conditions:</b>                                                             |                      |                             |                   |          |
| Phase                                                                                    | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                                      |                      |                             |                   |          |
| NPSH (ft):                                                                               | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                                    | 0.68                 | Allowable $\Delta P$ (psi): | 8.33              |          |
| Brake Power (hp):                                                                        | 0.97                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                                                | 0.65                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                                           | 2880                 | Head (ft):                  | 10                |          |

| A-101                                                                             |                      |                                |                    |           |
|-----------------------------------------------------------------------------------|----------------------|--------------------------------|--------------------|-----------|
| <b>Identification</b>                                                             | Item:                | Adsorption Column              |                    |           |
|                                                                                   | Item No:             | 1                              | Date:              | 05/05/20  |
|                                                                                   | No Required:         | 3                              |                    |           |
|                                                                                   | Total Purchase Cost: | \$110,265                      | Bare Module Cost:  | \$187,451 |
| <b>Function:</b> Removal of color forming components in the glucose syrup product |                      |                                |                    |           |
| <b>Operation:</b> Continuous process                                              |                      |                                |                    |           |
|                                                                                   | <b>Feed</b>          | <b>Product</b>                 |                    |           |
| <b>Materials Handled:</b>                                                         |                      |                                |                    |           |
| Total Flow (lb/hr):                                                               | 131,200              | 131,200                        |                    |           |
| Volumetric Flow (U.S. gallons/hr):                                                | 12,676               | 12,676                         |                    |           |
| <b>Component Flow (lb/hr):</b>                                                    |                      |                                |                    |           |
| Fructose                                                                          | 0                    | 0                              |                    |           |
| Glucose                                                                           | 62,320               | 62,320                         |                    |           |
| Oligosaccharides                                                                  | 3,280                | 3,280                          |                    |           |
| Water                                                                             | 65,600               | 65,600                         |                    |           |
| <b>Operating Conditions:</b>                                                      |                      |                                |                    |           |
| Phase                                                                             | Liquid               | Liquid                         |                    |           |
| Temperature (°F)                                                                  | 86                   | 86                             |                    |           |
| Pressure (psi)                                                                    | 6                    | 6                              |                    |           |
| <b>Design Data:</b>                                                               |                      |                                |                    |           |
| <b>Vessel</b>                                                                     |                      | <b>Vessel Internals</b>        |                    |           |
| Volume (ft <sup>3</sup> )                                                         | 390                  | Bed volume (ft <sup>3</sup> )  | 271                |           |
| Height (ft)                                                                       | 10.86                | Bed height (ft)                | 7.55               |           |
| Material                                                                          | SS 316               | Bed diameter (ft)              | 6.76               |           |
|                                                                                   |                      | Packing type                   | Macroporous Resins |           |
|                                                                                   |                      | Dry weight capacity (meq/g)    | 0.8                |           |
|                                                                                   |                      | Amount of Resin needed (lb)    | 17,425             |           |
|                                                                                   |                      | Resin regeneration time (mins) | 45                 |           |



| IX-101                                                                |                                                             |                                |                    |           |
|-----------------------------------------------------------------------|-------------------------------------------------------------|--------------------------------|--------------------|-----------|
| <b>Identification</b>                                                 | Item:                                                       | Strong Acid Cation Exchanger   |                    |           |
|                                                                       | Item No:                                                    | 1                              | Date:              | 05/05/20  |
|                                                                       | No Required:                                                | 3                              |                    |           |
|                                                                       | Total Purchase Cost:                                        | \$60,384                       | Bare Module Cost:  | \$102,653 |
| <b>Function:</b> Removal of mineral ions in the glucose syrup product |                                                             |                                |                    |           |
| <b>Operation:</b> Continuous process                                  |                                                             |                                |                    |           |
|                                                                       | <b>Feed</b>                                                 | <b>Product</b>                 |                    |           |
| <b>Materials Handled:</b>                                             |                                                             |                                |                    |           |
| Total Flow (lb/hr):                                                   | 131,200                                                     | 131,200                        |                    |           |
| Volumetric Flow (U.S. gallons/hr):                                    | 12,676                                                      | 12,676                         |                    |           |
| <b>Component Flow (lb/hr):</b>                                        |                                                             |                                |                    |           |
| Fructose                                                              | 0                                                           | 0                              |                    |           |
| Glucose                                                               | 62,320                                                      | 62,320                         |                    |           |
| Oligosaccharides                                                      | 3,280                                                       | 3,280                          |                    |           |
| Water                                                                 | 65,600                                                      | 65,600                         |                    |           |
| <b>Operating Conditions:</b>                                          |                                                             |                                |                    |           |
| Phase                                                                 | Liquid                                                      | Liquid                         |                    |           |
| Temperature (°F)                                                      | 86                                                          | 86                             |                    |           |
| Pressure (psi)                                                        | 6                                                           | 6                              |                    |           |
| <b>Design Data:</b>                                                   |                                                             |                                |                    |           |
| <b>Vessel</b>                                                         |                                                             | <b>Vessel Internals</b>        |                    |           |
| Volume (ft <sup>3</sup> )                                             | 112.6                                                       | Bed volume (ft <sup>3</sup> )  | 50.5               |           |
| Height (ft)                                                           | 11.7                                                        | Bed height (ft)                | 5.25               |           |
| Material                                                              | SS 316                                                      | Bed diameter (ft)              | 3.5                |           |
|                                                                       |                                                             | Packing type                   | Macroporous Resins |           |
|                                                                       |                                                             | Total exchange capacity (eq/L) | 1.8                |           |
|                                                                       |                                                             | Resin backwash                 | 80%                |           |
|                                                                       |                                                             | Amount of Resin needed (lb)    | 3,783              |           |
|                                                                       |                                                             | Resin regeneration time (mins) | 45                 |           |
| <b>Comments:</b>                                                      | 2 columns are running in series before the anion exchangers |                                |                    |           |

| IX-102                                                                |                                                             |                                |                    |           |
|-----------------------------------------------------------------------|-------------------------------------------------------------|--------------------------------|--------------------|-----------|
| <b>Identification</b>                                                 | Item:                                                       | Weak Base Anion Exchanger      |                    |           |
|                                                                       | Item No:                                                    | 2                              | Date:              | 05/05/20  |
|                                                                       | No Required:                                                | 3                              |                    |           |
|                                                                       | Total Purchase Cost:                                        | \$223,158                      | Bare Module Cost:  | \$379,369 |
| <b>Function:</b> Removal of mineral ions in the glucose syrup product |                                                             |                                |                    |           |
| <b>Operation:</b> Continuous process                                  |                                                             |                                |                    |           |
|                                                                       | <b>Feed</b>                                                 | <b>Product</b>                 |                    |           |
| <b>Materials Handled:</b>                                             |                                                             |                                |                    |           |
| Total Flow (lb/hr):                                                   | 131,200                                                     | 131,200                        |                    |           |
| Volumetric Flow (U.S. gallons/hr):                                    | 12,676                                                      | 12,676                         |                    |           |
| <b>Component Flow (lb/hr):</b>                                        |                                                             |                                |                    |           |
| Fructose                                                              | 0                                                           | 0                              |                    |           |
| Glucose                                                               | 62,320                                                      | 62,320                         |                    |           |
| Oligosaccharides                                                      | 3,280                                                       | 3,280                          |                    |           |
| Water                                                                 | 65,600                                                      | 65,600                         |                    |           |
| <b>Operating Conditions:</b>                                          |                                                             |                                |                    |           |
| Phase                                                                 | Liquid                                                      | Liquid                         |                    |           |
| Temperature (°F)                                                      | 86                                                          | 86                             |                    |           |
| Pressure (psi)                                                        | 6                                                           | 6                              |                    |           |
| <b>Design Data:</b>                                                   |                                                             |                                |                    |           |
| <b>Vessel</b>                                                         |                                                             | <b>Vessel Internals</b>        |                    |           |
| Volume (ft <sup>3</sup> )                                             | 934.8                                                       | Bed volume (ft <sup>3</sup> )  | 391.6              |           |
| Height (ft)                                                           | 25                                                          | Bed height (ft)                | 10.4               |           |
| Material                                                              | SS 316                                                      | Bed diameter (ft)              | 6.9                |           |
|                                                                       |                                                             | Packing type                   | Macroporous Resins |           |
|                                                                       |                                                             | Total exchange capacity (eq/L) | 1.5                |           |
|                                                                       |                                                             | Resin backwash                 | 100%               |           |
|                                                                       |                                                             | Amount of Resin needed (lb)    | 25,428             |           |
|                                                                       |                                                             | Resin regeneration time (mins) | 45                 |           |
| <b>Comments:</b>                                                      | 2 columns are running in series after the cation exchangers |                                |                    |           |



| P-106                                                                        |                      |                             |                   |          |
|------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                        | Item:                | Centrifugal Pump            |                   |          |
|                                                                              | Item No:             | 6                           | Date:             | 05/05/20 |
|                                                                              | No. Required:        | 2                           |                   |          |
|                                                                              | Total Purchase Cost: | \$13,882                    | Bare Module Cost: | \$45,811 |
| <b>Function:</b> Transportation of glucose syrup from ion exchanger to M-102 |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                         |                      |                             |                   |          |
|                                                                              | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                    |                      |                             |                   |          |
| Total Flow (lb/hr)                                                           | 131,200              | 131,200                     |                   |          |
| Volumetric Flow (U.S. Gallons/hr)                                            | 11,184               | 11,184                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                               |                      |                             |                   |          |
| Glucose                                                                      | 62,320               | 62,320                      |                   |          |
| Oligosaccharides                                                             | 3,280                | 3,280                       |                   |          |
| Water                                                                        | 65,600               | 65,600                      |                   |          |
| <b>Operating Conditions:</b>                                                 |                      |                             |                   |          |
| Phase:                                                                       | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                          |                      |                             |                   |          |
| NPSH (ft):                                                                   | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                        | 0.68                 | Allowable $\Delta P$ (psi): | 8.33              |          |
| Brake Power (hp):                                                            | 0.97                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                                    | 0.65                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                               | 2880                 | Head (ft):                  | 10                |          |

| M-102                                                  |                      |                                  |                   |           |
|--------------------------------------------------------|----------------------|----------------------------------|-------------------|-----------|
| <b>Identification</b>                                  | Item:                | Mixer                            |                   |           |
|                                                        | Item No:             | 2                                | Date:             | 05/05/20  |
|                                                        | No. Required:        | 1                                |                   |           |
|                                                        | Total Purchase Cost: | \$57,788                         | Bare Module Cost: | \$144,470 |
| <b>Function:</b> Change in pH and enzyme stabilization |                      |                                  |                   |           |
| <b>Operation:</b> Continuous process                   |                      |                                  |                   |           |
|                                                        | <b>Feed</b>          | <b>Product</b>                   |                   |           |
| <b>Materials Handled:</b>                              |                      |                                  |                   |           |
| Total Flow (lb/hr):                                    | 131,200              | 131,200                          |                   |           |
| Volumetric Flow (U.S. gallons/hr):                     | 11,184               | 11,184                           |                   |           |
| <b>Component Flow (lb/hr):</b>                         |                      |                                  |                   |           |
| Glucose                                                | 62,320               | 62,320                           |                   |           |
| Oligosaccharides                                       | 3,280                | 3,280                            |                   |           |
| Water                                                  | 65,600               | 65,600                           |                   |           |
| <b>Operating Conditions:</b>                           |                      |                                  |                   |           |
| Normal Operating Temp. (°F):                           | 77                   | Normal Operating Pressure (psi): | 14.7              |           |
| Max. Design Temp. (°F):                                | 127                  | Max. Design Pressure (psi):      | 150               |           |
| Min. Design Temp. (°F):                                | 52                   | Design Pressure (psi):           | 38.7              |           |
| Residence Time (mins):                                 | 5-10                 |                                  |                   |           |
| <b>Design Data:</b>                                    |                      |                                  |                   |           |
| Height (ft):                                           | 18                   | Material:                        | SS 316            |           |
| Diameter (ft):                                         | 4                    | Type of agitator:                | Gate Paddles      |           |
| Volume (ft³):                                          | 186                  | Diameter of agitator (ft):       | 3                 |           |
| Power Consumed (kW):                                   | 0.04                 | No. of impellers:                | 1                 |           |
|                                                        |                      | Orientation:                     | Vertical          |           |
| <b>Comments:</b>                                       | Open mixer vessel    |                                  |                   |           |





| P-107                                                                     |                      |                             |                   |          |
|---------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                     | Item:                | Centrifugal Pump            |                   |          |
|                                                                           | Item No:             | 7                           | Date:             | 05/05/20 |
|                                                                           | No. Required:        | 2                           |                   |          |
|                                                                           | Total Purchase Cost: | \$14,096                    | Bare Module Cost: | \$46,517 |
| <b>Function:</b> Transportation of glucose syrup from M-102 to evaporator |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                      |                      |                             |                   |          |
|                                                                           | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                 |                      |                             |                   |          |
| Total Flow (lb/hr)                                                        | 131,200              | 131,200                     |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                         | 11,184               | 11,184                      |                   |          |
| <b>Component Flow (lb/hr):</b>                                            |                      |                             |                   |          |
| Glucose                                                                   | 62,320               | 62,320                      |                   |          |
| Oligosaccharides                                                          | 3,280                | 3,280                       |                   |          |
| Water                                                                     | 65,600               | 65,600                      |                   |          |
| <b>Operating Conditions:</b>                                              |                      |                             |                   |          |
| Phase                                                                     | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                       |                      |                             |                   |          |
| NPSH (ft):                                                                | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                     | 0.69                 | Allowable $\Delta P$ (psi): | 8.33              |          |
| Brake Power (hp):                                                         | 0.98                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                                 | 0.66                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                            | 2880                 | Head (ft):                  | 10                |          |



| EY-101                                                        |                      |                   |                   |             |
|---------------------------------------------------------------|----------------------|-------------------|-------------------|-------------|
| <b>Identification</b>                                         | Item:                | Evaporator        |                   |             |
|                                                               | Item No:             | 1                 | Date:             | 05/05/20    |
|                                                               | No Required:         | 3                 |                   |             |
|                                                               | Total Purchase Cost: | \$1,806,387       | Bare Module Cost: | \$6,683,632 |
| <b>Function:</b> Concentration of glucose syrup               |                      |                   |                   |             |
| <b>Operation:</b> Continuous process                          |                      |                   |                   |             |
|                                                               | <b>Feed</b>          | <b>Product</b>    |                   |             |
| <b>Materials Handled:</b>                                     |                      |                   |                   |             |
| Total Flow (lb/hr):                                           | 131,200              | 131,200           |                   |             |
| Volumetric Flow (U.S. gallons/hr):                            | 11,184               | 11,184            |                   |             |
| <b>Component Flow (lb/hr):</b>                                | 62,320               | 62,320            |                   |             |
| Glucose                                                       | 3,280                | 3,280             |                   |             |
| Oligosaccharides                                              | 65,600               | 65,600            |                   |             |
| Water                                                         | 131,200              | 131,200           |                   |             |
| <b>Operating Conditions:</b>                                  |                      |                   |                   |             |
|                                                               | <b>Effect 1</b>      | <b>Effect 2</b>   | <b>Effect 3</b>   |             |
| Overall heat transfer coefficient (Btu/hr* $\text{ft}^2$ *°F) | 550                  | 350               | 200               |             |
| Temperature (°F)                                              | 227                  | 188               | 121               |             |
| Pressure (psi)                                                | 29                   | 14.7              | 1.89              |             |
| Steam temperature (°F)                                        | 248                  | 221               | 180               |             |
| Heat duty (Btu/hr)                                            | $2.1 \times 10^7$    | $1.3 \times 10^7$ | $1.6 \times 10^7$ |             |
| <b>Design Data:</b>                                           |                      |                   |                   |             |
| Type                                                          | Forced Circulation   |                   |                   |             |
| Method of operation                                           | Triple Effect        |                   |                   |             |
| Residence time (minutes)                                      | 25                   |                   |                   |             |
| Area ( $\text{ft}^2$ )                                        | 1421                 | 1421              | 1421              |             |
| Steam economy                                                 | 2.25                 |                   |                   |             |
| Material                                                      | SS 316               |                   |                   |             |



| E-103                                           |                            |                |                   |           |
|-------------------------------------------------|----------------------------|----------------|-------------------|-----------|
| <b>Identification</b>                           | Item:                      | Condenser      |                   |           |
|                                                 | Item No:                   | 1              | Date:             | 05/05/20  |
|                                                 | No Required:               | 1              |                   |           |
|                                                 | Total Purchase Cost:       | \$40,208       | Bare Module Cost: | \$120,624 |
| <b>Function:</b> Concentration of glucose syrup |                            |                |                   |           |
| <b>Operation:</b> Continuous process            |                            |                |                   |           |
|                                                 | <b>Feed</b>                | <b>Product</b> |                   |           |
| <b>Materials Handled:</b>                       |                            |                |                   |           |
| Total Flow (lb/hr):                             | 49,200                     | 49,200         |                   |           |
| Volumetric Flow (U.S. gallons/hr):              | 5,896                      | 5,896          |                   |           |
| <b>Component Flow (lb/hr):</b>                  |                            |                |                   |           |
| Glucose                                         | -                          | -              |                   |           |
| Oligosaccharides                                | -                          | -              |                   |           |
| Water                                           | 49,200                     | 49,200         |                   |           |
| <b>Operating Conditions:</b>                    |                            |                |                   |           |
| Phase                                           | Vapor                      | Liquid         |                   |           |
| Pressure (psi)                                  | 14.7                       | 14.7           |                   |           |
| Heat load (Btu/hr)                              | $2 \times 10^7$            |                |                   |           |
| Vapor temperature (°F)                          | 111.43                     | 77             |                   |           |
| Cooling water temperature (°F)                  | 85                         | 96.8           |                   |           |
| Water consumption (lb water/lb vapor)           | 540                        |                |                   |           |
| <b>Design Data:</b>                             |                            |                |                   |           |
| Type                                            | Counter-current barometric |                |                   |           |
| Material                                        | Carbon Steel               |                |                   |           |
| Diameter (ft)                                   | 49                         |                |                   |           |
| Height (ft)                                     | 34                         |                |                   |           |
| Area (ft <sup>2</sup> )                         | 2434                       |                |                   |           |

| P-109                                                                   |                      |                             |                   |          |
|-------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                   | Item:                | Centrifugal Pump            |                   |          |
|                                                                         | Item No:             | 9                           | Date:             | 05/05/20 |
|                                                                         | No. Required:        | 2                           |                   |          |
|                                                                         | Total Purchase Cost: | \$14,416                    | Bare Module Cost: | \$47,573 |
| <b>Function:</b> Transportation of glucose syrup from evaporator to PBR |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                    |                      |                             |                   |          |
|                                                                         | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                               |                      |                             |                   |          |
| Total Flow (lb/hr)                                                      | 82,000               | 82,000                      |                   |          |
| Volumetric Flow (U.S. Gallons/hr)                                       | 2,906                | 2,906                       |                   |          |
| <b>Component Flow (lb/hr):</b>                                          |                      |                             |                   |          |
| Glucose                                                                 | 62,320               | 62,320                      |                   |          |
| Oligosaccharides                                                        | 3,280                | 3,280                       |                   |          |
| Water                                                                   | 16,400               | 16,400                      |                   |          |
| <b>Operating Conditions:</b>                                            |                      |                             |                   |          |
| Phase                                                                   | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                     |                      |                             |                   |          |
| NPSH (ft):                                                              | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                   | 1.70                 | Allowable $\Delta P$ (psi): | 57.24             |          |
| Brake Power (hp):                                                       | 2.10                 | Efficiency (%):             | 78                |          |
| Shaft work required (kW):                                               | 1.50                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                          | 2880                 | Head (ft):                  | 39                |          |





| R-103                                                 |                                                          |                               |                   |             |
|-------------------------------------------------------|----------------------------------------------------------|-------------------------------|-------------------|-------------|
| <b>Identification</b>                                 | Item:                                                    | Packed Bed Reactor            |                   |             |
|                                                       | Item No:                                                 | 3                             | Date:             | 05/05/20    |
|                                                       | No Required:                                             | 21                            |                   |             |
|                                                       | Total Purchase Cost:                                     | \$1,287,300                   | Bare Module Cost: | \$5,149,200 |
| <b>Function:</b> Isomerization of glucose to fructose |                                                          |                               |                   |             |
| <b>Operation:</b> Continuous process                  |                                                          |                               |                   |             |
|                                                       | <b>Feed</b>                                              | <b>Product</b>                |                   |             |
| <b>Materials Handled:</b>                             |                                                          |                               |                   |             |
| Total Flow (lb/hr):                                   | 86,000                                                   | 86,000                        |                   |             |
| Volumetric Flow (U.S. gallons/hr):                    | 7,334                                                    | 7,334                         |                   |             |
| <b>Component Flow (lb/hr):</b>                        |                                                          |                               |                   |             |
| Fructose                                              | -                                                        | 27,100                        |                   |             |
| Glucose                                               | 65,300                                                   | 35,500                        |                   |             |
| Oligosaccharides                                      | 3,300                                                    | 1,900                         |                   |             |
| Water                                                 | 17,400                                                   | 21,500                        |                   |             |
| <b>Operating Conditions:</b>                          |                                                          |                               |                   |             |
| Phase                                                 | Liquid                                                   | Liquid                        |                   |             |
| Temperature (°F)                                      | 121                                                      | 140                           |                   |             |
| Pressure (psi)                                        | 14.7                                                     | 14.7                          |                   |             |
| Residence time (hours)                                | 4                                                        |                               |                   |             |
| <b>Design Data:</b>                                   |                                                          |                               |                   |             |
| <b>Vessel</b>                                         |                                                          | <b>Vessel Internals</b>       |                   |             |
| Volume (ft <sup>3</sup> )                             | 477                                                      | Bed volume (ft <sup>3</sup> ) | 283               |             |
| Height (ft)                                           | 20                                                       | Bed height (ft)               | 17                |             |
| Outer diameter (ft)                                   | 5                                                        | Bed diameter (ft)             | 4.94              |             |
| Wall thickness (ft)                                   | 0.03                                                     | Catalyst weight (lb)          | 8,450             |             |
| Pressure drop (psi)                                   | 2                                                        | Pellet shape                  | Cylindrical beads |             |
| Material                                              | SS 316                                                   | Catalyst life (days)          | 235               |             |
| Heating medium                                        | Hot water                                                |                               |                   |             |
| Heat duty (Btu/hr)                                    | 34,639                                                   |                               |                   |             |
| Hot water flow (lb/hr)                                | 68,200                                                   |                               |                   |             |
| <b>Comments:</b>                                      | 14 reactors are running in parallel<br>7 backup reactors |                               |                   |             |

| P-110                                                               |                      |                             |                   |          |
|---------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                               | Item:                | Centrifugal Pump            |                   |          |
|                                                                     | Item No:             | 10                          | Date:             | 05/05/20 |
|                                                                     | No. Required:        | 2                           |                   |          |
|                                                                     | Total Purchase Cost: | \$16,800                    | Bare Module Cost: | \$55,440 |
| <b>Function:</b> Transports HFCS 42 syrup from PBR to ion exchanger |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                |                      |                             |                   |          |
|                                                                     | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                           |                      |                             |                   |          |
| Total Flow (lb/hr)                                                  | 86,000               | 86,000                      |                   |          |
| Volumetric Flow (U.S. Gallons/hr)                                   | 7,334                | 7,334                       |                   |          |
| <b>Component Flow (lb/hr):</b>                                      |                      |                             |                   |          |
| Fructose                                                            | 27,100               | 27,100                      |                   |          |
| Glucose                                                             | 35,500               | 35,500                      |                   |          |
| Oligosaccharides                                                    | 1,900                | 1,900                       |                   |          |
| Water                                                               | 21,500               | 21,500                      |                   |          |
| <b>Operating Conditions:</b>                                        |                      |                             |                   |          |
| Phase                                                               | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                 |                      |                             |                   |          |
| NPSH (ft):                                                          | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                               | 1.0                  | Allowable $\Delta P$ (psi): | 31.29             |          |
| Brake Power (hp):                                                   | 1.3                  | Efficiency (%):             | 77                |          |
| Shaft work required (kW):                                           | 4.5                  | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                      | 1880                 | Head (ft):                  | 23                |          |



| IX-103                                                          |                                                             |                                |                    |          |
|-----------------------------------------------------------------|-------------------------------------------------------------|--------------------------------|--------------------|----------|
| <b>Identification</b>                                           | Item:                                                       | Strong Acid Cation Exchanger   |                    |          |
|                                                                 | Item No:                                                    | 3                              | Date:              | 05/05/20 |
|                                                                 | No Required:                                                | 3                              |                    |          |
|                                                                 | Total Purchase Cost:                                        | \$48,000                       | Bare Module Cost:  | \$81,600 |
| <b>Function:</b> Removal of mineral ions in the HFCS 42 product |                                                             |                                |                    |          |
| <b>Operation:</b> Continuous process                            |                                                             |                                |                    |          |
|                                                                 | <b>Feed</b>                                                 | <b>Product</b>                 |                    |          |
| <b>Materials Handled:</b>                                       |                                                             |                                |                    |          |
| Total Flow (lb/hr):                                             | 86,000                                                      | 86,000                         |                    |          |
| Volumetric Flow (U.S. gallons/hr):                              | 7658                                                        | 7658                           |                    |          |
| <b>Component Flow (lb/hr):</b>                                  |                                                             |                                |                    |          |
| Fructose                                                        | 27,100                                                      | 27,100                         |                    |          |
| Glucose                                                         | 35,500                                                      | 35,500                         |                    |          |
| Oligosaccharides                                                | 1,900                                                       | 1,900                          |                    |          |
| Water                                                           | 21,500                                                      | 21,500                         |                    |          |
| <b>Operating Conditions:</b>                                    |                                                             |                                |                    |          |
| Phase                                                           | Liquid                                                      | Liquid                         |                    |          |
| Temperature (°F)                                                | 140                                                         | 140                            |                    |          |
| Pressure (psi)                                                  | 24                                                          | 24                             |                    |          |
| <b>Design Data:</b>                                             |                                                             |                                |                    |          |
| <b>Vessel</b>                                                   |                                                             | <b>Vessel Internals</b>        |                    |          |
| Volume (ft³)                                                    | 57.3                                                        | Bed volume (ft³)               | 23                 |          |
| Height (ft)                                                     | 10                                                          | Bed height (ft)                | 4                  |          |
| Material                                                        | SS 316                                                      | Bed diameter (ft)              | 2.7                |          |
|                                                                 |                                                             | Packing type                   | Macroporous Resins |          |
|                                                                 |                                                             | Total exchange capacity (eq/L) | 1.8                |          |
|                                                                 |                                                             | Resin backwash                 | 90%                |          |
|                                                                 |                                                             | Amount of Resin needed (lb)    | 1728               |          |
|                                                                 |                                                             | Resin regeneration time (mins) | 45                 |          |
| <b>Comments:</b>                                                | 2 columns are running in series before the anion exchangers |                                |                    |          |

| EX-104                                                          |                                                             |                                |                    |           |
|-----------------------------------------------------------------|-------------------------------------------------------------|--------------------------------|--------------------|-----------|
| <b>Identification</b>                                           | Item:                                                       | Weak Base Anion Exchanger      |                    |           |
|                                                                 | Item No:                                                    | 4                              | Date:              | 05/05/20  |
|                                                                 | No Required:                                                | 3                              |                    |           |
|                                                                 | Total Purchase Cost:                                        | \$93,000                       | Bare Module Cost:  | \$158,100 |
| <b>Function:</b> Removal of mineral ions in the HFCS 42 product |                                                             |                                |                    |           |
| <b>Operation:</b> Continuous process                            |                                                             |                                |                    |           |
|                                                                 | <b>Feed</b>                                                 | <b>Product</b>                 |                    |           |
| <b>Materials Handled:</b>                                       |                                                             |                                |                    |           |
| Total Flow (lb/hr):                                             | 86,000                                                      | 86,000                         |                    |           |
| Volumetric Flow (U.S. gallons/hr):                              | 7658                                                        | 7658                           |                    |           |
| <b>Component Flow (lb/hr):</b>                                  |                                                             |                                |                    |           |
| Fructose                                                        | 27,100                                                      | 27,100                         |                    |           |
| Glucose                                                         | 35,500                                                      | 35,500                         |                    |           |
| Oligosaccharides                                                | 1,900                                                       | 1,900                          |                    |           |
| Water                                                           | 21,500                                                      | 21,500                         |                    |           |
| <b>Operating Conditions:</b>                                    |                                                             |                                |                    |           |
| Phase                                                           | Liquid                                                      | Liquid                         |                    |           |
| Temperature (°F)                                                | 140                                                         | 140                            |                    |           |
| Pressure (psi)                                                  | 20                                                          | 20                             |                    |           |
| <b>Design Data:</b>                                             |                                                             |                                |                    |           |
| <b>Vessel</b>                                                   |                                                             | <b>Vessel Internals</b>        |                    |           |
| Volume (ft³)                                                    | 235.6                                                       | Bed volume (ft³)               | 93.23              |           |
| Height (ft)                                                     | 16.3                                                        | Bed height (ft)                | 6.46               |           |
| Material                                                        | SS 316                                                      | Bed diameter (ft)              | 4.29               |           |
|                                                                 |                                                             | Packing type                   | Macroporous Resins |           |
|                                                                 |                                                             | Total exchange capacity (eq/L) | 1.5                |           |
|                                                                 |                                                             | Resin backwash                 | 100%               |           |
|                                                                 |                                                             | Amount of Resin needed (lb)    | 6053               |           |
|                                                                 |                                                             | Resin regeneration time (mins) | 45                 |           |
| <b>Comments:</b>                                                | 2 columns are running in series after the cation exchangers |                                |                    |           |



| P-112                                                                               |                      |                             |                   |          |
|-------------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                               | Item:                | Centrifugal Pump            |                   |          |
|                                                                                     | Item No:             | 12                          | Date:             | 05/05/20 |
|                                                                                     | No. Required:        | 2                           |                   |          |
|                                                                                     | Total Purchase Cost: | \$16,800                    | Bare Module Cost: | \$55,440 |
| <b>Function:</b> Transportation of HFCS 42 syrup from ion exchanger to storage tank |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                                |                      |                             |                   |          |
|                                                                                     | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                           |                      |                             |                   |          |
| Total Flow (lb/hr)                                                                  | 86,000               | 86,000                      |                   |          |
| Volumetric Flow (U.S. Gallons/hr)                                                   | 7,334                | 7,334                       |                   |          |
| <b>Component Flow (lb/hr):</b>                                                      |                      |                             |                   |          |
| Fructose                                                                            | 27,100               | 27,100                      |                   |          |
| Glucose                                                                             | 35,500               | 35,500                      |                   |          |
| Oligosaccharides                                                                    | 1,900                | 1,900                       |                   |          |
| Water                                                                               | 21,500               | 21,500                      |                   |          |
| <b>Operation Conditions:</b>                                                        |                      |                             |                   |          |
| Phase                                                                               | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                                 |                      |                             |                   |          |
| NPSH (ft):                                                                          | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                               | 0.13                 | Allowable $\Delta P$ (psi): | 4.88              |          |
| Brake Power (hp):                                                                   | 0.17                 | Efficiency (%):             | 76                |          |
| Shaft work required (kW):                                                           | 0.13                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                                      | 1700                 | Head (ft):                  | 6                 |          |

| P-113                                                              |                      |                             |                   |          |
|--------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                              | Item:                | Centrifugal Pump            |                   |          |
|                                                                    | Item No:             | 13                          | Date:             | 05/05/20 |
|                                                                    | No. Required:        | 2                           |                   |          |
|                                                                    | Total Purchase Cost: | \$11,700                    | Bare Module Cost: | \$38,610 |
| <b>Function:</b> Transportation of HFCS 42 syrup into storage tank |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                               |                      |                             |                   |          |
|                                                                    | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                          |                      |                             |                   |          |
| Total Flow (lb/hr)                                                 | 86,000               | 86,000                      |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                  | 7,334                | 7,334                       |                   |          |
| <b>Component Flow (lb/hr):</b>                                     |                      |                             |                   |          |
| Fructose                                                           | 27,100               | 27,100                      |                   |          |
| Glucose                                                            | 35,500               | 35,500                      |                   |          |
| Oligosaccharides                                                   | 1,900                | 1,900                       |                   |          |
| Water                                                              | 21,500               | 21,500                      |                   |          |
| <b>Operation Conditions:</b>                                       |                      |                             |                   |          |
| Phase                                                              | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                |                      |                             |                   |          |
| NPSH (ft):                                                         | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                              | 0.13                 | Allowable $\Delta P$ (psi): | 4.88              |          |
| Brake Power (hp):                                                  | 0.17                 | Efficiency (%):             | 76                |          |
| Shaft work required (kW):                                          | 0.13                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                     | 1700                 | Head (ft):                  | 6                 |          |





| CC-101                                                           |                                                               |                                   |                   |           |
|------------------------------------------------------------------|---------------------------------------------------------------|-----------------------------------|-------------------|-----------|
| <b>Identification</b>                                            | Item:                                                         | Chromatography Column             |                   |           |
|                                                                  | Item No:                                                      | 1                                 | Date:             | 05/05/20  |
|                                                                  | No Required:                                                  | 16                                |                   |           |
|                                                                  | Total Purchase Cost:                                          | \$224,000                         | Bare Module Cost: | \$380,800 |
| <b>Function:</b> Enrichment of fructose concentration in HFCS 42 |                                                               |                                   |                   |           |
| <b>Operation:</b> Continuous process                             |                                                               |                                   |                   |           |
|                                                                  | <b>Feed</b>                                                   | <b>Product</b>                    |                   |           |
| <b>Materials Handled:</b>                                        |                                                               |                                   |                   |           |
| Total Flow (lb/hr):                                              | 15,030                                                        | 15,030                            |                   |           |
| Volumetric Flow<br>(U.S. gallons/hr):                            | 712.4                                                         | 712.4                             |                   |           |
| <b>Component Flow<br/>(lb/hr):</b>                               |                                                               |                                   |                   |           |
| Fructose                                                         | 2,520                                                         | 8,200                             |                   |           |
| Glucose                                                          | 3,300                                                         | 3,290                             |                   |           |
| Oligosaccharides                                                 | 180                                                           | 640                               |                   |           |
| Water                                                            | 9,030                                                         | 2,900                             |                   |           |
| <b>Operating Conditions:</b>                                     |                                                               |                                   |                   |           |
| Phase                                                            | Liquid                                                        | Liquid                            |                   |           |
| Temperature (°F)                                                 | 140                                                           | 140                               |                   |           |
| Pressure (psi)                                                   | 15.1                                                          | 13                                |                   |           |
| <b>Design Data:</b>                                              |                                                               |                                   |                   |           |
| <b>Vessel</b>                                                    |                                                               | <b>Vessel Internals</b>           |                   |           |
| Volume (ft <sup>3</sup> )                                        | 63                                                            | Bed volume (ft <sup>3</sup> )     | 29                |           |
| Height (ft)                                                      | 9                                                             | Bed height (ft)                   | 4.1               |           |
| Material                                                         | SS 316                                                        | Bed diameter (ft)                 | 3                 |           |
|                                                                  |                                                               | Packing type                      | Gel Resins        |           |
|                                                                  |                                                               | Resin backwash                    | 70%               |           |
|                                                                  |                                                               | Amount of Resin needed<br>(lb)    | 4985              |           |
|                                                                  |                                                               | Resin regeneration time<br>(mins) | 45                |           |
|                                                                  |                                                               | Switching time                    | 78                |           |
|                                                                  |                                                               | Peak Resolution                   | 3.5               |           |
| <b>Comments:</b>                                                 | Simulated Moving Bed approach is used with 12 columns running |                                   |                   |           |

| P-114                                                                |                      |                             |                   |          |
|----------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                | Item:                | Centrifugal Pump            |                   |          |
|                                                                      | Item No:             | 14                          | Date:             | 05/05/20 |
|                                                                      | No. Required:        | 2                           |                   |          |
|                                                                      | Total Purchase Cost: | \$16,800                    | Bare Module Cost: | \$55,440 |
| <b>Function:</b> Transportation of HFCS 42 from split point to M-103 |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                 |                      |                             |                   |          |
|                                                                      | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                            |                      |                             |                   |          |
| Total Flow (lb/hr)                                                   | 35,000               | 35,000                      |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                    | 2,985                | 2,985                       |                   |          |
| <b>Component Flow (lb/hr):</b>                                       |                      |                             |                   |          |
| Fructose                                                             | 11,040               | 11,040                      |                   |          |
| Glucose                                                              | 14,430               | 14,430                      |                   |          |
| Oligosaccharides                                                     | 790                  | 790                         |                   |          |
| Water                                                                | 8,740                | 8,740                       |                   |          |
| <b>Operating Conditions:</b>                                         |                      |                             |                   |          |
| Phase                                                                | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                  |                      |                             |                   |          |
| NPSH (ft):                                                           | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                | 0.72                 | Allowable $\Delta P$ (psi): | 192.13            |          |
| Brake Power (hp):                                                    | 1.01                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                            | 0.73                 | Impeller Size (inch):       | 5                 |          |
| Impeller specific speed (rpm):                                       | 4000                 | Head (ft):                  | 131               |          |



| P-115                                                                          |                      |                             |                   |          |
|--------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                          | Item:                | Centrifugal Pump            |                   |          |
|                                                                                | Item No:             | 15                          | Date:             | 05/05/20 |
|                                                                                | No. Required:        | 2                           |                   |          |
|                                                                                | Total Purchase Cost: | \$10,420                    | Bare Module Cost: | \$34,386 |
| <b>Function:</b> Transportation of HFCS 90 from chromatography column to M-103 |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                           |                      |                             |                   |          |
|                                                                                | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                      |                      |                             |                   |          |
| Total Flow (lb/hr)                                                             | 11,000               | 11,000                      |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                              | 938                  | 938                         |                   |          |
| <b>Component Flow (lb/hr):</b>                                                 |                      |                             |                   |          |
| Fructose                                                                       | 8,200                | 8,200                       |                   |          |
| Glucose                                                                        | 270                  | 270                         |                   |          |
| Oligosaccharides                                                               | 640                  | 640                         |                   |          |
| Water                                                                          | 1,890                | 1,890                       |                   |          |
| <b>Operating Conditions:</b>                                                   |                      |                             |                   |          |
| Phase                                                                          | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                            |                      |                             |                   |          |
| NPSH (ft):                                                                     | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                          | 0.72                 | Allowable $\Delta P$ (psi): | 192.13            |          |
| Brake Power (hp):                                                              | 1.01                 | Efficiency (%):             | 70                |          |
| Shaft work required (kW):                                                      | 0.73                 | Impeller Size (in):         | 5                 |          |
| Impeller specific speed (rpm):                                                 | 4000                 | Head (ft):                  | 131               |          |

|                                                                      |                  |                     |                 |  |
|----------------------------------------------------------------------|------------------|---------------------|-----------------|--|
| Identification                                                       |                  |                     |                 |  |
| Item:                                                                | Centrifugal Pump |                     |                 |  |
| Item No:                                                             | 16               | Date:               | 05/05/20        |  |
| No. Required:                                                        | 2                |                     |                 |  |
| Total Purchase Cost:                                                 | \$14,420         | Bare Module Cost:   | \$47,586        |  |
| Function: Transportation of HFCS 55 syrup from M-103 to storage tank |                  |                     |                 |  |
| Operation: Continuous process                                        |                  |                     |                 |  |
|                                                                      | Feed             | Product             |                 |  |
| Materials Handled:                                                   |                  |                     |                 |  |
| Total Flow (lb/hr)                                                   | 46,000           | 46,000              |                 |  |
| Volumetric Flow (U.S. gallons/hr)                                    | 3,922            | 3,922               |                 |  |
| Component Flow (lb/hr):                                              |                  |                     |                 |  |
| Fructose                                                             | 19,000           | 19,000              |                 |  |
| Glucose                                                              | 14,500           | 14,500              |                 |  |
| Oligosaccharides                                                     | 1,000            | 1,000               |                 |  |
| Water                                                                | 11,500           | 11,500              |                 |  |
| Operating Conditions:                                                |                  |                     |                 |  |
| Phase                                                                | Liquid           | Liquid              |                 |  |
| Design Data:                                                         |                  |                     |                 |  |
| NPSH (ft):                                                           | 5-25             | Material:           | Carbon Steel 45 |  |
| Hydraulic Power (hp):                                                | 1.40             | Allowable ΔP(psi):  | 0.2             |  |
| Brake Power (hp):                                                    | 1.88             | Efficiency (%):     | 76              |  |
| Shaft work required (kW):                                            | 1.50             | Impeller Size (in): | 5               |  |
| Impeller specific speed (rpm):                                       | 2000             | Head (ft):          | 62              |  |



| P-117                                                                                    |                      |                             |                   |          |
|------------------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|----------|
| <b>Identification</b>                                                                    | Item:                | Centrifugal Pump            |                   |          |
|                                                                                          | Item No:             | 17                          | Date:             | 05/05/20 |
|                                                                                          | No. Required:        | 2                           |                   |          |
|                                                                                          | Total Purchase Cost: | \$10,420                    | Bare Module Cost: | \$34,386 |
| <b>Function:</b> Transportation of unconverted glucose from liquid chromatography to PBR |                      |                             |                   |          |
| <b>Operation:</b> Continuous process                                                     |                      |                             |                   |          |
|                                                                                          | <b>Feed</b>          | <b>Product</b>              |                   |          |
| <b>Materials Handled:</b>                                                                |                      |                             |                   |          |
| Total Flow (lb/hr)                                                                       | 4,030                | 4,030                       |                   |          |
| Volumetric Flow (U.S. gallons/hr)                                                        | 344                  | 344                         |                   |          |
| <b>Component Flow (lb/hr):</b>                                                           |                      |                             |                   |          |
| Unconverted Glucose                                                                      | 3,020                | 3,020                       |                   |          |
| Water                                                                                    | 1,010                | 1,010                       |                   |          |
| <b>Operating Conditions:</b>                                                             |                      |                             |                   |          |
| Phase                                                                                    | Liquid               | Liquid                      |                   |          |
| <b>Design Data:</b>                                                                      |                      |                             |                   |          |
| NPSH (ft):                                                                               | 5-25                 | Material:                   | Carbon Steel 45   |          |
| Hydraulic Power (hp):                                                                    | 0.10                 | Allowable $\Delta P$ (psi): | 36                |          |
| Brake Power (hp):                                                                        | 0.11                 | Efficiency (%):             | 55                |          |
| Shaft work required (kW):                                                                | 0.10                 | Head (ft):                  | 30                |          |
| Impeller Speed (rpm):                                                                    | 2000                 | Impeller Size (in):         | 5                 |          |



| M-103                                                         |                      |                                  |                        |           |
|---------------------------------------------------------------|----------------------|----------------------------------|------------------------|-----------|
| <b>Identification</b>                                         | Item:                | Mixer                            |                        |           |
|                                                               | Item No:             | 3                                | Date:                  | 05/05/20  |
|                                                               | No. Required:        | 1                                |                        |           |
|                                                               | Total Purchase Cost: | \$40,763                         | Bare Module Cost:      | \$101,908 |
| <b>Function:</b> Mixing HFCS 90 and HFC 42 to produce HFCS 55 |                      |                                  |                        |           |
| <b>Operation:</b> Continuous process                          |                      |                                  |                        |           |
|                                                               | <b>HFCS 90 Feed</b>  | <b>HFCS 42 Feed</b>              | <b>HFCS 55 Product</b> |           |
| <b>Materials Handled:</b>                                     |                      |                                  |                        |           |
| Total Flow (lb/hr):                                           | 11,000               | 35,000                           | 46,000                 |           |
| Volumetric Flow (U.S. gallons/hr):                            | 938                  | 2985                             | 3922                   |           |
| <b>Component Flow (lb/hr):</b>                                |                      |                                  |                        |           |
| Fructose                                                      | 8,200                | 11,040                           | 19,000                 |           |
| Glucose                                                       | 270                  | 14,430                           | 14,500                 |           |
| Oligosaccharides                                              | 640                  | 790                              | 1,000                  |           |
| Water                                                         | 1,890                | 8,740                            | 11,500                 |           |
| <b>Operating Conditions:</b>                                  |                      |                                  |                        |           |
| Normal Operating Temp. (°F):                                  | 77                   | Normal Operating Pressure (psi): | 14.7                   |           |
| Max. Design Temp. (°F):                                       | 127                  | Max. Design Pressure (psi):      | 150                    |           |
| Min. Design Temp. (°F):                                       | 52                   | Design Pressure (psi):           | 38.7                   |           |
| Residence Time (mins):                                        | 5-10                 |                                  |                        |           |
| <b>Design Data:</b>                                           |                      |                                  |                        |           |
| Height (ft):                                                  | 6                    | Material:                        | SS 316                 |           |
| Diameter (ft):                                                | 3                    | Type of agitator:                | Gate Paddles           |           |
| Volume (ft³):                                                 | 36                   | Diameter of agitator (ft):       | 1                      |           |
| Power Consumed (kW):                                          | 0.32                 | No. of impellers:                | 1                      |           |
|                                                               |                      | Orientation:                     | Vertical               |           |
| <b>Comments:</b>                                              | Open mixer vessel    |                                  |                        |           |



| E-104                                                          |                      |                                  |                      |           |
|----------------------------------------------------------------|----------------------|----------------------------------|----------------------|-----------|
| <b>Identification</b>                                          | Item:                | Shell and Tube Heat Exchanger    |                      |           |
|                                                                | Item No:             | 4                                | Date:                | 05/05/20  |
|                                                                | No. Required:        | 2                                |                      |           |
|                                                                | Total Purchase Cost: | \$41,850                         | Bare Module Cost:    | \$132,665 |
| <b>Function:</b> Cooling HFCS 42 product stream for storage    |                      |                                  |                      |           |
| <b>Operation:</b> Continuous process                           |                      |                                  |                      |           |
|                                                                | <b>Tube Side</b>     | <b>Shell Side</b>                |                      |           |
| <b>Materials Handled:</b>                                      |                      |                                  |                      |           |
| Total Flow (lb/hr):                                            | 43,000               | 43,000                           |                      |           |
| Volumetric Flow (U.S. gallons/hr):                             | 3,666                | 3,666                            |                      |           |
| <b>Component Flow (lb/hr):</b>                                 |                      |                                  |                      |           |
| Fructose                                                       | 13,545               | 13,545                           |                      |           |
| Glucose                                                        | 17,738               | 17,738                           |                      |           |
| Oligosaccharides                                               | 967                  | 967                              |                      |           |
| Water                                                          | 22,200               | 1,287                            |                      |           |
| <b>Operating Conditions:</b>                                   |                      |                                  |                      |           |
| Normal Operating Temp. (°F):                                   | 68-140               | Normal Operating Pressure (psi): | 14.7                 |           |
| Max. Operating Temp. (°F):                                     | 190                  | Max. Operating Pressure (psi):   | 40                   |           |
| Min. Operating Temp. (°F):                                     | 43                   | Design Operating Pressure (psi): | 65                   |           |
| <b>Design Data:</b>                                            |                      |                                  |                      |           |
| Heat Transfer Area (ft <sup>2</sup> ):                         | 310                  | Material:                        | SS 316               |           |
| $\Delta T_{LM}$ (°F):                                          | 36                   | Shell Diameter(in):              | 21.25                |           |
| Shell-Tube Arrangement:                                        | 2-4                  | Tube Outside Diameter(in):       | 0.75 on 1" Triangles |           |
| Heat required (kW):                                            | 490                  | Tube Count:                      | 326                  |           |
| Overall Heat Transfer Coefficient (Btu/hr-ft <sup>2</sup> -R): | 150                  | TEMA Config.:                    | AEL                  |           |



| 10-105                                                         |                      |                                  |                      |           |
|----------------------------------------------------------------|----------------------|----------------------------------|----------------------|-----------|
| <b>Identification</b>                                          | Item:                | Shell and Tube Heat Exchanger    |                      |           |
|                                                                | Item No:             | 2                                | Date:                | 05/05/20  |
|                                                                | No. Required:        | 2                                |                      |           |
|                                                                | Total Purchase Cost: | \$41,850                         | Bare Module Cost:    | \$132,665 |
| <b>Function:</b> Cooling HFCS-55 product stream for storage    |                      |                                  |                      |           |
| <b>Operation:</b> Continuous process                           |                      |                                  |                      |           |
|                                                                | <b>Tube Side</b>     | <b>Shell Side</b>                |                      |           |
| <b>Materials Handled:</b>                                      |                      |                                  |                      |           |
| Total Flow (lb/hr):                                            | 46,000               | 46,000                           |                      |           |
| Volumetric Flow (U.S. gallons/hr):                             | 3,922                | 3,922                            |                      |           |
| <b>Component Flow (lb/hr):</b>                                 |                      |                                  |                      |           |
| Fructose                                                       | 19,000               | 19,000                           |                      |           |
| Glucose                                                        | 14,500               | 14,500                           |                      |           |
| Oligosaccharides                                               | 1,000                | 1,000                            |                      |           |
| Water                                                          | 11,500               | 11,500                           |                      |           |
| <b>Operating Conditions:</b>                                   |                      |                                  |                      |           |
| Normal Operating Temp. (°F):                                   | 68-140               | Normal Operating Pressure (psi): | 14.7                 |           |
| Max. Operating Temp. (°F):                                     | 190                  | Max. Operating Pressure (psi):   | 40                   |           |
| Min. Operating Temp. (°F):                                     | 43                   | Design Operating Pressure (psi): | 65                   |           |
| <b>Design Data:</b>                                            |                      |                                  |                      |           |
| Heat Transfer Area (ft <sup>2</sup> ):                         | 310                  | Material:                        | SS 316               |           |
| $\Delta T_{LM}$ (°F):                                          | 36                   | Shell Diameter(in):              | 21.25                |           |
| Shell-Tube Arrangement:                                        | 2-4                  | Tube Outside Diameter(in):       | 0.75 on 1" Triangles |           |
| Heat required (kW):                                            | 470                  | Tube Count:                      | 326                  |           |
| Overall Heat Transfer Coefficient (Btu/hr-ft <sup>2</sup> -R): | 150                  | TEMA Config:                     | AEL                  |           |



| TK-102                                            |                                                                       |                                  |                   |             |
|---------------------------------------------------|-----------------------------------------------------------------------|----------------------------------|-------------------|-------------|
| <b>Identification</b>                             | Item:                                                                 | Tank                             |                   |             |
|                                                   | Item No:                                                              | 5                                | Date:             | 05/05/20    |
|                                                   | No. Required:                                                         | 29                               |                   |             |
|                                                   | Total Purchase Cost:                                                  | \$580,000                        | Bare Module Cost: | \$2,320,000 |
| <b>Function:</b> Holding tank for HFCS 42 product |                                                                       |                                  |                   |             |
| <b>Operation:</b> Continuous process              |                                                                       |                                  |                   |             |
|                                                   | <b>Feed</b>                                                           | <b>Product</b>                   |                   |             |
| <b>Materials Handled:</b>                         |                                                                       |                                  |                   |             |
| Total Flow (lb/hr):                               | 43,000                                                                | 43,000                           |                   |             |
| Volumetric Flow (U.S. gallons/hr):                | 3,665                                                                 | 3,665                            |                   |             |
| <b>Component Flow (lb/hr):</b>                    |                                                                       |                                  |                   |             |
| Fructose                                          | 13,545                                                                | 13,545                           |                   |             |
| Glucose                                           | 17,738                                                                | 17,738                           |                   |             |
| Oligosaccharides                                  | 967                                                                   | 967                              |                   |             |
| Water                                             | 10,750                                                                | 10,750                           |                   |             |
| <b>Operating Conditions:</b>                      |                                                                       |                                  |                   |             |
| Phase                                             | Liquid                                                                | Liquid                           |                   |             |
| Normal Operating Temperature (°F):                | 81                                                                    | Normal Operating Pressure (psi): | 14                |             |
| Max. Operating Temperature (°F):                  | 127                                                                   | Max. Operating Pressure (psi):   | 150               |             |
| Min. Operating Temperature (°F):                  | 52                                                                    | Design Operating Pressure (psi): | 30                |             |
| <b>Design Data:</b>                               |                                                                       |                                  |                   |             |
| Orientation:                                      | Vertical                                                              | Material:                        | SS 316            |             |
| Height (ft):                                      | 16                                                                    | Type:                            | Conical Roof      |             |
| Diameter (ft):                                    | 9                                                                     | Volume (U.S. gallons):           | 15,000            |             |
| <b>Comments:</b>                                  | Holds about 3 days' worth of syrup before transport to final consumer |                                  |                   |             |

| TK-103                                            |                                                                       |                                  |                   |             |
|---------------------------------------------------|-----------------------------------------------------------------------|----------------------------------|-------------------|-------------|
| <b>Identification</b>                             | Item:                                                                 | Tank                             |                   |             |
|                                                   | Item No:                                                              | 5                                | Date:             | 05/05/20    |
|                                                   | No. Required:                                                         | 30                               |                   |             |
|                                                   | Total Purchase Cost:                                                  | \$600,000                        | Bare Module Cost: | \$2,400,000 |
| <b>Function:</b> Holding tank for HFCS 55 product |                                                                       |                                  |                   |             |
| <b>Operation:</b> Continuous process              |                                                                       |                                  |                   |             |
|                                                   | <b>Feed</b>                                                           | <b>Product</b>                   |                   |             |
| <b>Materials Handled:</b>                         |                                                                       |                                  |                   |             |
| Total Flow (lb/hr):                               | 46,000                                                                | 46,000                           |                   |             |
| Volumetric Flow (U.S. gallons/hr):                | 3,922                                                                 | 3,922                            |                   |             |
| <b>Component Flow (lb/hr):</b>                    |                                                                       |                                  |                   |             |
| Fructose                                          | 19,000                                                                | 19,000                           |                   |             |
| Glucose                                           | 14,500                                                                | 14,500                           |                   |             |
| Oligosaccharides                                  | 1,000                                                                 | 1,000                            |                   |             |
| Water                                             | 11,500                                                                | 11,500                           |                   |             |
| <b>Operating Conditions:</b>                      |                                                                       |                                  |                   |             |
| Phase                                             | Liquid                                                                | Liquid                           |                   |             |
| Normal Operating Temperature (°F):                | 81                                                                    | Normal Operating Pressure (psi): | 14                |             |
| Max. Operating Temperature (°F):                  | 127                                                                   | Max. Operating Pressure (psi):   | 150               |             |
| Min. Operating Temperature (°F):                  | 52                                                                    | Design Operating Pressure (psi): | 30                |             |
| <b>Design Data:</b>                               |                                                                       |                                  |                   |             |
| Orientation:                                      | Vertical                                                              | Material:                        | SS 316            |             |
| Height (ft):                                      | 16                                                                    | Type:                            | Conical Roof      |             |
| Diameter (ft):                                    | 9                                                                     | Volume (U.S. gallons):           | 15,000            |             |
| <b>Comments:</b>                                  | Holds about 3 days' worth of syrup before transport to final consumer |                                  |                   |             |





## 8. ECONOMIC EVALUATION

### 8.1 Capital Cost

#### 8.1.1 Fixed Capital Investment

The bare model cost of the main equipment involved in this design is shown in Table 8.1 below.

Table 8.1 Equipment Summary List

| UNIT   | Unit Type             | Unit Purchase Cost (\$) | No | Total Purchase Cost (\$) | Bare Module Factor | Bare Module Cost (\$) |
|--------|-----------------------|-------------------------|----|--------------------------|--------------------|-----------------------|
| CY-101 | Pneumatic Conveyor    | 72,809                  | 1  | 72,809                   | 2.2                | 160,180               |
| M-101  | Mixer                 | 15,290                  | 1  | 15,290                   | 2.5                | 38,225                |
| TK-101 | Tank                  | 5,300                   | 1  | 5,300                    | 3                  | 15,900                |
| JC-101 | Jet Cooker            | 454                     | 1  | 454                      | 4                  | 1,816                 |
| P-101  | Pump                  | 4,485                   | 2  | 8,970                    | 3.3                | 29,601                |
| P-102  | Pump                  | 107,029                 | 2  | 214,058                  | 3.3                | 706,391               |
| P-103  | Pump                  | 2,083                   | 2  | 4,165                    | 3.3                | 13,745                |
| P-104  | Pump                  | 2,643                   | 2  | 5,286                    | 3.3                | 17,444                |
| E-101  | Cooler                | 23,674                  | 2  | 47,348                   | 3.17               | 150,093               |
| R-101  | Reactor               | 75,000                  | 7  | 525,000                  | 3                  | 1,575,000             |
| R-102  | Reactor               | 400,000                 | 29 | 11,600,000               | 3                  | 34,800,000            |
| F-101  | Vacuum Rotary Filter  | 252,252                 | 1  | 252,252                  | 3.6                | 908,107               |
| CY-102 | Conveyor Belt         | 11,704                  | 1  | 11,704                   | 2.4                | 28,090                |
| WT-101 | Waste Vessel          | 385,090                 | 2  | 770,180                  | 3                  | 2,310,540             |
| P-105  | Pump                  | 6,941                   | 2  | 13,882                   | 3.3                | 45,811                |
| A-101  | Adsorption Column     | 36,755                  | 3  | 110,265                  | 1.7                | 187,451               |
| IX-101 | Cation Exchanger      | 20,128                  | 3  | 60,384                   | 1.7                | 102,653               |
| IX-102 | Anion Exchanger       | 74,386                  | 3  | 223,158                  | 1.7                | 379,369               |
| P-106  | Pump                  | 6,941                   | 2  | 13,882                   | 3.3                | 45,811                |
| M-102  | Mixer                 | 57,788                  | 1  | 57,788                   | 2.5                | 144,470               |
| P-107  | Pump                  | 7,048                   | 2  | 14,096                   | 3.3                | 46,517                |
| EV-101 | Evaporator            | 602,129                 | 3  | 1,806,387                | 3.7                | 6,683,632             |
| E-103  | Condenser             | 40,208                  | 1  | 40,208                   | 3                  | 120,624               |
| P-108  | Pump                  | 8,009                   | 2  | 16,018                   | 3.3                | 52,859                |
| P-109  | Pump                  | 7,208                   | 2  | 14,416                   | 3.3                | 47,573                |
| R-103  | Reactor               | 61,300                  | 21 | 1,287,300                | 4                  | 5,149,200             |
| P-110  | Pump                  | 8,400                   | 2  | 16,800                   | 3.3                | 55,440                |
| IX-103 | Cation Exchanger      | 16,000                  | 3  | 48,000                   | 1.7                | 81,600                |
| P-111  | Pump                  | 8,400                   | 2  | 16,800                   | 3.3                | 55,440                |
| IX-104 | Anion Exchanger       | 31,000                  | 3  | 93,000                   | 1.7                | 158,100               |
| P-112  | Pump                  | 8,400                   | 2  | 16,800                   | 3.3                | 55,440                |
| CC-101 | Chromatography Column | 14,000                  | 16 | 224,000                  | 1.7                | 380,800               |
| P-113  | Pump                  | 5,850                   | 2  | 11,700                   | 3.3                | 38,610                |
| P-114  | Pump                  | 8,400                   | 2  | 16,800                   | 3.3                | 55,440                |
| E-104  | Cooler                | 20,925                  | 2  | 41,850                   | 3.17               | 132,665               |
| E-105  | Cooler                | 20,925                  | 2  | 41,850                   | 3.17               | 132,665               |
| P-115  | Pump                  | 5,210                   | 2  | 10,420                   | 3.3                | 34,386                |
| P-116  | Pump                  | 7,210                   | 2  | 14,420                   | 3.3                | 47,586                |
| M-103  | Mixer                 | 40,763                  | 1  | 40,763                   | 2.5                | 101,908               |
| TK-102 | Storage Tank          | 20,000                  | 29 | 580,000                  | 4                  | 2,320,000             |
| TK-103 | Storage Tank          | 20,000                  | 30 | 600,000                  | 4                  | 2,400,000             |
|        | Water treatment       |                         | 1  |                          |                    | 500,000               |
|        |                       |                         |    | \$ 18,948,513            |                    | \$ 60,311,182         |

Font

The unit purchase costs were obtained from tables and graphs published by *Turton, et al.* 2018 and *Ulrich 1984* and adjusted to the 2019 cost index value of 540. The total purchase cost was obtained for the total number of equipment and the bare module cost was obtained by multiplying this value by the corresponding bare module factors. The bare module factors were also obtained from *Turton, et al. 2018* and *Ulrich 1984* to give a total bare module cost of about \$60.4 million. This value was used to obtain the total module cost by multiplying the value by 1.18, giving a total module cost of about \$73 million. This value was also used as the fixed capital investment cost (FCI) to determine the cost of manufacturing for the project.

what is this called?

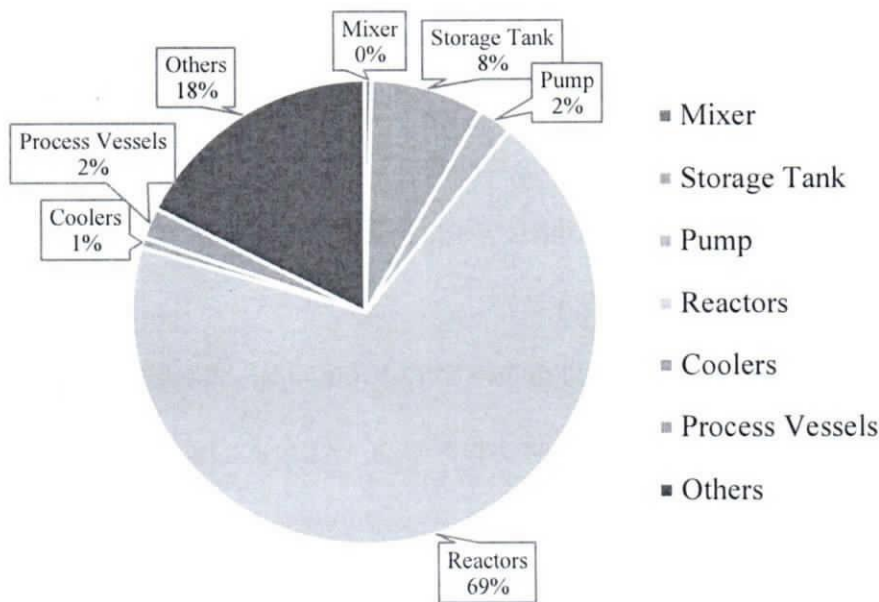


Figure 8.1 Breakdown of Major Equipment Cost

From Figure 8.1 above, the majority of the equipment costs are associated with the reactors in the process. The next major costs are associated with the cost of conveyors, filters, jet cooker, and waste handling with the bulk of this cost deriving from the water treatment plant.



*This section  
is weak  
on specifics.*

### 8.1.2 Working Capital

The working capital for this project was obtained from the fixed capital investment. It was assumed that the working capital which involves the costs of storage of raw materials and products, salaries, payable taxes, etc. was 20% of the fixed capital investment value (Turton 248). This value was obtained to be \$14.6 million.

### 8.1.3 Total Capital Investment

Total Capital Investment (TCI) is the sum of the fixed capital investment and the working capital. For this project, the value of TCI was calculated to be \$88 million.

## 8.2 Operating Cost

The cost of manufacturing encompasses direct and fixed manufacturing costs as well as general expenses. This was calculated using Equation 8.1 below where  $C_{OL}$ ,  $C_{UT}$ ,  $C_{WT}$ ,  $C_{RM}$  represent the cost of operating labor, utilities, waste treatment, and raw materials respectively.

$$COM = 0.280FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \quad (8.1)$$

The value for this project was calculated to give \$112.5 million and this takes depreciation into account. The cost of manufacturing without depreciation  $COM_d$  can be calculated using Equation 8.2 below.

$$COM_d = 0.180FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \quad (8.2)$$

The value for this project was calculated to be \$105 million and this value was used to generate the cumulative cash flow diagram.

Some main categories of the manufacturing costs are shown in Table 8.2 below. This shows the cost breakdown of the elements that influence the cost of manufacturing.

Table 8.2 Summary of Manufacturing Costs

| Item                         | Cost (\$million/yr) |
|------------------------------|---------------------|
| <b>VARIABLE COST</b>         |                     |
| Raw materials                | 50.0                |
| Utilities                    | 15.0                |
| Waste Treatment              | 1.4                 |
| Packaging and Shipping       | 0.2                 |
| <b>Total</b>                 | <b>66.6</b>         |
| <b>FIXED COST</b>            |                     |
| Operating labor              | 3.8                 |
| Operating supervision        | 0.6                 |
| Salaries Overhead            | 2.2                 |
| Maintenance and repairs      | 4.4                 |
| Taxes (property) & Insurance | 2.3                 |
| Land                         | 0.4                 |
| Royalties                    | 3.4                 |
| Plant overhead, general      | 5.3                 |
| <b>Total</b>                 | <b>22.4</b>         |
| <b>GENERAL EXPENSES</b>      |                     |
| Administration               | 1.7                 |
| Distribution & selling       | 8.7                 |
| Research & Development       | 7.0                 |
| <b>Total</b>                 | <b>17.4</b>         |

ok

### Cost of Raw Materials

The cost of materials represents the bulk of the variable costs (about 75%) and this value includes the cost of other process consumables such as catalysts, resins, acids, and bases. The main raw material required for this process is corn starch and a unit purchase cost of \$0.46/lb was used (Tate&Lyle). About 157,000 lbs are used annually, therefore, the annual cost of corn starch purchase is \$8 million. The cost of the acids and bases were obtained to be \$16,000. The cost of all catalysts was obtained from the list price of Creative Enzymes Inc. and given to be



\$40.6 million annually. Finally, the resins costs were obtained from the list price of DOWEX resins and given to be \$2 million annually.

### **Cost of Utility**

Table 8.3 gives the factors that contribute to the total annual cost of utilities for the process.

Table 8.3 Summary of Process Utilities

|                 |                     |
|-----------------|---------------------|
| Electricity     | \$10,069,488        |
| Steam           | \$4,036,890         |
| Water           | \$409,591           |
| Waste Treatment | \$1,425,282         |
| <b>TOTAL</b>    | <b>\$15,941,251</b> |



Electricity represents the greatest of these costs and this is because the power consumption by the evaporator and condenser are high and this is in addition to other electricity requirements through the process. The total annual power usage for the process is 23,982 kW and the power cost is \$0.053/kWh, therefore giving an annual electricity cost to be \$10 million. The steam used in this process is culinary steam because it is required for food-grade production and the unit purchase cost was given to be \$0.004/lb for an annual amount of 940 million lbs. The water cost includes the cost of process water treatment, cooling water for the coolers and vessel jackets, and hot water to give an annual cost of about \$410,000. The cost of waste treatment is derived from the cost of treating waste involved in catalyst and resin regeneration to give an annual cost of \$1.4 million.

### **Cost of Operating Labor**

The cost of operating labor was determined by the number of operators per unit as determined by the Bureau of Labor Statistics. A factor of 4.5 was multiplied by the number of operators needed for each equipment to obtain the total cost of operating labor. For the overall process, a total of



64 operators working 8-hour shifts are needed and this gives an annual cost of operating labor of \$3.8 million.

### 8.3 Project Analysis

There are three sources of revenue generation for this project, sales of HFCS 42, HFCS 55, and the waste feed from the rotary filter which is sold as wet corn gluten feed. The sales price for both HFCS products were obtained from the United States Department of Agriculture. The sales price for both HFCS 42 and HFCS 55 used to calculate the revenue are the wholesale spot prices for both products as of April 2020 which were 25.5 ¢/lb and 32.75 ¢/lb respectively (USDA). Given an annual output of 333 million pounds for HFCS 42 and 364 million pounds for HFCS 55, the annual revenue generated for each was calculated to be \$85 million for HFCS 42 and \$119 million for HFCS 55. The sales price for the corn gluten feed was taken to be \$0.04/lb and for an annual output of 115 million pounds, the annual revenue generated from this was calculated to be \$4.6 million. This gives a total annual revenue of about \$209 million.

The gross profit obtained was calculated by subtracting the sum of all fixed and variable costs from the main product revenues. The variable costs of production were calculated to be about \$62 million and the fixed costs of production were calculated to be \$ 22.3 million. Since HFCS 42 and HFCS 55 are considered the main products, the total revenue generated from them is \$204 million. The annual gross profit was then calculated to be about \$120 million. The net profit was calculated from this value by subtracting the value of taxes. A tax rate of 48% was used for this project which includes federal, state tax for Iowa, and city tax for Asbury, Iowa. With this value, the annual taxes were calculated to be \$57.5 million and this gave an annual net profit of \$62.3 million.

*This is extremely high!!*



The non-discounted and discounted cumulative cash flow for the project was generated and is shown in Figure 8.2.

| n=20 years      | i=0.48             | i=0.1                      | FCI=\$72,972,900 | WC=\$14,594,580        | Land=\$388,302                          | R=\$208,756,310     |                         |                      |                      |                                 |
|-----------------|--------------------|----------------------------|------------------|------------------------|-----------------------------------------|---------------------|-------------------------|----------------------|----------------------|---------------------------------|
| End of year (k) | Capital Investment | Depreciation Allowance (d) | [FCIL - sum(dk)] | Revenue from sales (R) | Discounted Cost of Manufacturing (COMd) | After-Tax Cash Flow | Nondiscounted Cash Flow | Cumulative Cash Flow | Discounted Cash Flow | Cumulative Discounted Cash Flow |
| 0               | (388,302)          | -                          | 72,972,900       | -                      | -                                       | -                   | (388,302)               | (388,302)            | (388,302)            | (388,302)                       |
| 1               | (43,783,740)       | -                          | 72,972,900       | -                      | -                                       | -                   | (43,783,740)            | (44,172,042)         | (39,803,400)         | (40,191,702)                    |
| 2               | (14,594,580)       | -                          | 72,972,900       | -                      | -                                       | -                   | (14,594,580)            | (58,766,622)         | (12,061,636)         | (52,253,338)                    |
| 3               | -                  | 14,594,580                 | 58,378,320       | 104,378,155            | 105,234,400                             | 6,560,151           | 6,560,151               | (52,206,471)         | 4,928,739            | (47,324,600)                    |
| 4               | -                  | 23,351,328                 | 35,026,992       | 187,880,679            | 105,234,400                             | 54,184,703          | 54,184,703              | 1,978,232            | 37,008,881           | (10,315,719)                    |
| 5               | -                  | 14,010,797                 | 21,016,195       | 208,756,310            | 105,234,400                             | 60,556,576          | 60,556,576              | 62,534,807           | 37,600,869           | 27,285,150                      |
| 6               | -                  | 8,391,884                  | 12,624,312       | 208,756,310            | 105,234,400                             | 57,859,497          | 57,859,497              | 120,394,304          | 32,660,178           | 59,945,328                      |
| 7               | -                  | 8,391,884                  | 4,232,428        | 208,756,310            | 105,234,400                             | 57,859,497          | 57,859,497              | 178,253,802          | 29,691,071           | 89,636,399                      |
| 8               | -                  | 4,232,428                  | -                | 208,756,310            | 105,234,400                             | 55,862,959          | 55,862,959              | 234,116,760          | 26,060,483           | 115,696,881                     |
| 9               | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 287,948,154          | 22,829,766           | 138,526,647                     |
| 10              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 341,779,547          | 20,754,332           | 159,280,979                     |
| 11              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 395,610,940          | 18,867,575           | 178,148,554                     |
| 12              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 449,442,333          | 17,152,341           | 195,300,895                     |
| 13              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 503,273,726          | 15,593,037           | 210,893,932                     |
| 14              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 557,105,120          | 14,175,488           | 225,069,420                     |
| 15              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 610,936,513          | 12,886,808           | 237,956,228                     |
| 16              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 664,767,906          | 11,715,280           | 249,671,508                     |
| 17              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 718,599,299          | 10,650,254           | 260,321,762                     |
| 18              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 772,430,692          | 9,682,049            | 270,003,811                     |
| 19              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 826,262,086          | 8,801,863            | 278,805,674                     |
| 20              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 880,093,479          | 8,001,694            | 286,807,368                     |
| 21              | -                  | -                          | -                | 208,756,310            | 105,234,400                             | 53,831,393          | 53,831,393              | 933,924,872          | 7,274,267            | 294,081,634                     |
| 22              | 14,982,882         | -                          | -                | 209,144,612            | 105,234,400                             | 54,033,310          | 69,016,192              | 1,002,941,064        | 8,478,361            | 302,559,996                     |
| TOTALS          |                    | \$ 72,972,900              |                  | \$ 4,050,260,716       |                                         | \$ 1,046,724,802    |                         |                      | \$ 302,559,998       |                                 |

Figure 8.2 Cumulative Discounted Cash Flow

A plant life of 20 years was used for this analysis with the first two years for plant construction and start-up. A discount rate of 10% was applied and the Modified Accelerated Cost Recovery System (MACRS) was used to determine the depreciation allowance using a 5-year recovery period. A ramp-up revenue generation was used with the first year of revenue generation running at 50% capacity, the second year of generation running at 90% capacity before 100% capacity is used till the end of the plant life. The cumulative discounted cashflow values gave negative values until year 5 where it became positive. At the end of the plant life, the net present value from the cumulative discounted cash flow was about \$303 million. The cash flow diagram is

represented in Figure 8.3 below. It shows that the break-even point is after year 4 indicating that profit can be made early on in the project.

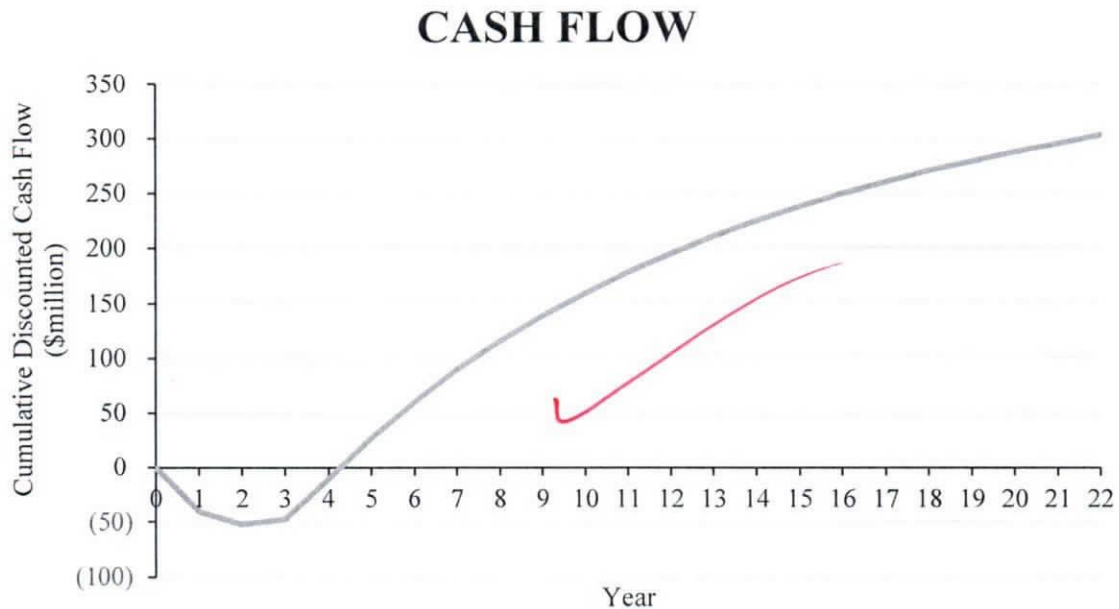


Figure 8.3 Cash Flow Diagram

The present value ratio was calculated to be 6.79 which is much greater than 1 which is an indication that the process is profitable (Turton 271). The return on investment (ROI) was calculated by dividing annual net profit by the fixed capital investment to give a value of 85.3% with a discounted payback period (DPBP) of 2 years. The discounted cash flow rate of return (DCFROR) represents the value discount rate for which the net positive value is 0 and this value was calculated to be 49.6%. A project is considered profitable if the DCFROR is greater than the internal discount rate (Turton 273) and 49.6% is greater than 10%, therefore, this is another indication that this project is profitable. Since the payback period is relatively short for the great return on investment, this project overall is highly profitable.



## 9. SAFETY AND HAZOP ANALYSIS

### 9.1 Hazard and Operability (HAZOP) Study

The vessel selected for this HAZOP study is the packed bed reactor (R-103). This reactor is responsible for the conversion of glucose in the incoming glucose syrup to fructose to give High Fructose Corn Syrup containing 42% fructose through an isomerization reaction. Two lines will be considered for this analysis and the details are represented in HAZOP tables. A piping and instrumentation diagram (P&ID) diagram showing the control scheme for the operation of this reactor is represented in Figure 9.1 below.

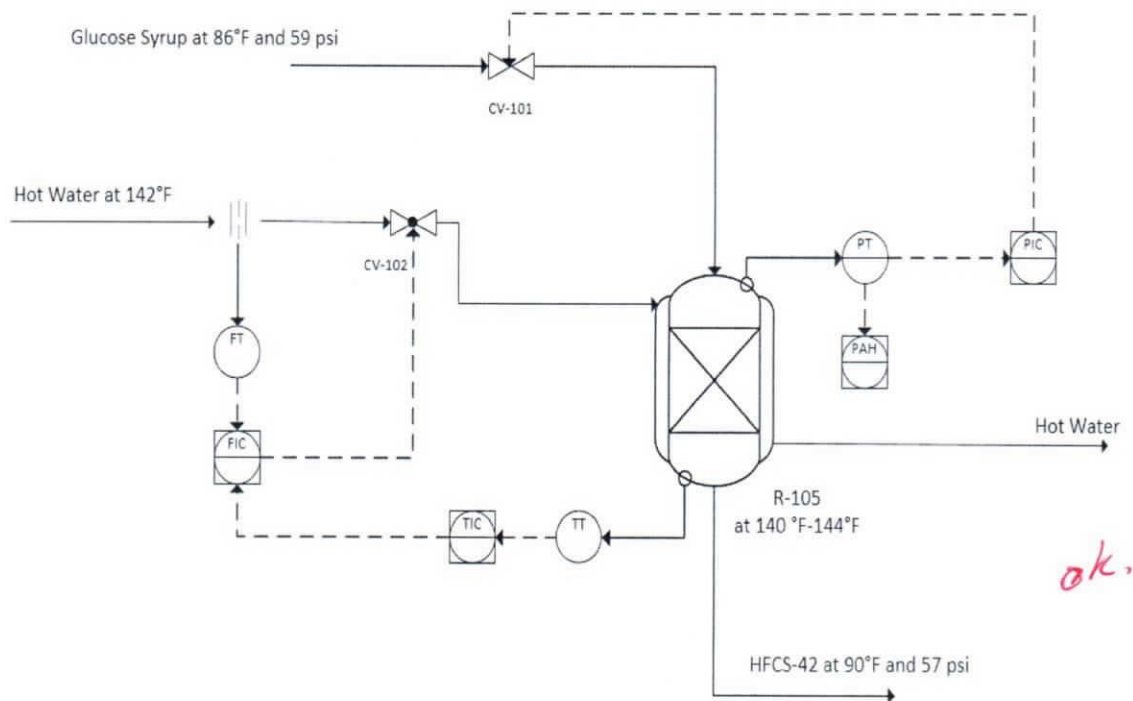


Figure 9.1 Control Scheme for the Packed Bed Reactor (R-103)



*why control two parameters??*

The control scheme for the packed bed reactor is centered around controlling the internal column pressure and temperature. For the temperature, the desired set point is 140°F which is required for optimum enzyme activity. The temperature is to be controlled by manipulating the flow rate of hot water into the vessel jacket. An orifice measures the flow of the hot water and is connected to the flow transmitter which sends a signal to the flow indicator controller. A temperature transmitter on the vessel sends the temperature reading to the temperature indicator controller which sends the signal to the flow indicator controller as well. The flow indicator controller gives the go-ahead to the globe valve on the hot water feed stream to open or shut depending on if the reactor temperature is too low and more hot water needs to be fed or if the reactor temperature is too high and the flow of hot water is to be stopped or slowed.

For the internal pressure control, the desired set point is 14 psi. The pressure build-up is caused by a blockage in the fluid path through the packed bed. Blockage can be enhanced when the enzyme pellets become crushed due to the higher-pressure condition within the reactor. A pressure transmitter is put in place to record the internal reactor pressure at any given time. The signal is sent to the pressure indicator controller which triggers the gate valve on the glucose syrup feed stream to shut off if the pressure recorded exceeds the setpoint. A high-pressure alarm is also installed as an extra precautionary measure. The reading from the pressure transmitter is also sent to the high-pressure alarm. In the case where the pressure indicator controller or the gate valve is faulty or clogged, the alarm will go off if a pressure around the maximum allowable working pressure for the reactor is sensed. A distributed control system is used for the plant, hence, the gate valve on the glucose feed stream can be automatically manipulated once the high-pressure alarm goes off. The HAZOP analysis is shown below in Table 9.1 and Table 9.2.





Table 9.1 HAZOP Analysis on Line 35 of HFCS Production Plant

| Study Node                                       | Keyword  | Guide Word | Deviation                                            | Cause                   | Consequences                                                                                                                                              | Action                                                                                                                                                                                                                                                                                             |
|--------------------------------------------------|----------|------------|------------------------------------------------------|-------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Line 35<br>(incoming<br>Glucose<br>syrup stream) | Flow     | No         | No flow of<br>glucose syrup<br>through<br>packed bed | Blocked<br>catalyst bed | 1. No<br>isomerization<br>reaction<br>2. Desired<br>product<br>(HFCS 42) not<br>formed<br>3.                                                              | 1. Unclog reactor<br>packed bed                                                                                                                                                                                                                                                                    |
|                                                  | Pressure | More       | Pressure in<br>reactor above<br>14 psi               | Blocked<br>catalyst bed | 1. Pressure<br>buildup in the<br>reactor<br>2. Enzymes get<br>crushed<br>leading to<br>more flow<br>blockage<br>3. Increased<br>chance of an<br>explosion | 1. Install<br>pressure<br>transmitter to<br>signal the<br>pressure<br>controller and<br>shut off valve<br>2. Shut off<br>glucose syrup<br>flow<br>3. Install high<br>pressure alarm<br>system to alert<br>operator<br>4. Pressure relief<br>valve<br>discharges<br>5. Unclog reactor<br>packed bed |

Table 9.2 HAZOP analysis on line 55 of HFCS Production Plant

| Study Node                                       | Keyword     | Guide Word | Deviation                          | Cause                              | Consequences                                                                                                                                                                                                                  | Action                                                                                                                                                                                                                                   |
|--------------------------------------------------|-------------|------------|------------------------------------|------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Line 55<br>(Hot water stream for cooling jacket) | Temperature | High       | Temperature in reactor above 158°F | Excessive flow of heating fluid    | <ol style="list-style-type: none"> <li>1. Slower reaction rate due to denaturation of enzyme</li> <li>2. Lower yield of fructose in product stream</li> <li>3. Compromised product quality due to enzyme poisoning</li> </ol> | <ol style="list-style-type: none"> <li>1. Install temperature transmitter to record reactor temperature</li> <li>2. Install flow meter to record hot water flow rate</li> <li>3. Set up controllers to control valve function</li> </ol> |
|                                                  |             | Low        | Temperature in reactor below 140°F | Insufficient flow of heating fluid | <ol style="list-style-type: none"> <li>1. Compromised product quality due to enzyme poisoning</li> </ol>                                                                                                                      |                                                                                                                                                                                                                                          |

## 9.2 Safety Considerations

One concern in this plant is the accumulation of combustible dust. The causes of these include the release of grain dust during loading, cooling, transferring, and storage. The dust can cause explosions when in contact with an ignition source. Ignition sources range from a hot bearing on the belt conveyor, smoldering materials caught in the dust collection system, to electrostatic discharge from process equipment (Oregon OSHA). Controls to mitigate dust explosions are as follows:

- Use dust collection to collect any dust that may be released in the air.
- Use automatic systems to detect sparks and smoldering materials.
- Equipment prone to electrostatic discharge is properly grounded and bonded.
- A fire detection system in dust collectors and other equipment prone to fire



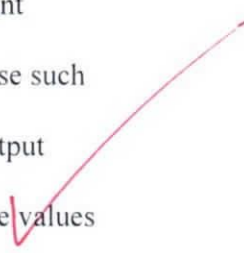
- Install explosion relief venting system.
- Routine maintenance of ventilation systems
- No smoking in or near this area.
- Keep hot work away from potential dust accumulation.

Furthermore, the handling of hazardous materials such as hydrochloric acid and sodium hydroxide. These materials are corrosive and considered irritants to the skin. The vapors from said materials are toxic to the human body. In order to avoid any potential hazards, ventilation systems are to be put in place. Additionally, proper personal protective equipment must be worn in the process and storage areas where hazardous materials are used or stored (Oregon OSHA).

## 10. DISCUSSION

### 10.1 Assumptions for Calculations

To derive the output stream flows for HFCS 42 and HFCS 55, the typical plant capacity was converted to metric tons per hour (41.6 tons/hr) and then to pounds per hour (91,700 lbs/hr). Of this amount, the assumption that 50% of plant production is HFCS 55 and 46% of plant production is HFCS 42 was used. The rest was assumed to be HFCS for miscellaneous use such as in pharmaceuticals or agriculture (Venkatasubramania 142). With the values of the output stream, further calculations were made with including some assumptions to determine the values of the anterior streams. These assumptions, however, will be presented in order of the first unit to the last unit. For the first stirred, it was assumed that a 30% w/w solid solution must be leaving because a higher solid concentration would be harder to move through the pump. It was assumed that a 20% w/w solid solution left the jet cooker as the slurry became more gelatinized due to the contact with culinary steam in the cooker. Calculations for the first stirred tank reactor were



made assuming. The liquefaction product typically has a dextrose equivalent (DE) of 10-15% (Buchholz 494) and 10% was used for calculations. After the liquefaction, the saccharification product was assumed to be a 50% w/w solid solution with a 95% DE (Buchholz 496). It was assumed that all ash was lost in the deashing and decolorization steps although, in reality, a very small amount makes its way to the final HFCS products. The final ash amount is so small it was assumed negligible for calculations in this design. It was also assumed that a 50% w/w solid product exited this unit. After evaporation, it was assumed that the concentrated product had an 80% w/w solid composition. In the packed bed reactor, a conversion of 42% was used for calculations. This value ideally is 50%, however, in practical applications, this value is usually in the range of 90% of the theoretical maximum (Illanes 200). It was also assumed that all streams exiting this unit contained a 75% w/w solid composition. After isomerization, it was assumed that 50% of the HFCS 42 produced went to the storage tank and the other half went to a split point. At this split point, 81.6% of the syrup (HFCS 42) goes straight to the final mixer where it is blended with the HFCS 90 from the chromatography column is to give the HFCS 55. It was assumed that the syrup leaving the final mixer had a solid composition of 75% w/w. These product stream solids composition was based on the specification that commercial-grade HFCS must have a solids concentration of no less than 70% (Schenck 18).

## 10.2 Discussion

The degrees of freedom analysis for the units give values greater than zero but no more than 5. This is a good range of values to allow for better design flexibility which aids the optimization process after the design has been completed. After the degrees of freedom analysis, an overall material balance for the process was performed. The input streams consist of the water streams (freshwater and process water) and starch stream into the first mixer and the freshwater

did you perform any optimization?



fed to the chromatography column. The output streams consist of the process waste feed from the rotary drum filter and the HFCS 42 and 55 output streams. The input and output totals are 104,030 lb/hr and 103,478 lb/hr and these values are in a very close range with a difference of 0.5%. A possible cause for the slight difference in output and input totals could be the assumptions used in making the calculations. In simulating the process on ASPEN, there were some limitations in component and equipment packages, for example, undefined starch properties as well as the absence of library models to properly simulate processes like the ion exchange and chromatography. To combat this, the flowsheet was truncated using subroutines to obtain a simplified flowsheet that converged. The results of the converged flowsheet in Table 6.1 showed that there was a difference of about 0.62% and 0.65% in the results of the simulated flow rates compared to the hand calculations for HFCS 42 and HFCS 55 respectively. From the economic analysis performed for the plant, a longer plant life, a lower discount rate, and fewer depreciation recovery years altogether give a greater net present value for the plant at the end of its life. The process is generally safe with the most hazardous components being the acid and salt solutions used occasionally for pH control and enzyme activation. Dust explosions from the corn starch could also occur and for these reasons, appropriate precautionary measures are implemented and emphasized such as the installation of an explosion relief system and the use of appropriate personal protective equipment.



## 11. CONCLUSIONS AND RECOMMENDATIONS

A detailed design and economic analysis of a high fructose corn syrup (HFCS) plant with a capacity of 706 MMlbs/year was accomplished for this project. All equipment was properly designed and sized to accommodate the total yearly capacity. From the detailed design performed on each equipment, the total cost of equipment needed for this project was obtained and that value was used to determine the Fixed Capital Investment (FCI) amount needed to start the project. In addition to this, the yearly capital and operating cost for a plant life of twenty years was calculated. A discounted cumulative cash flow was obtained, and a detailed economic analysis was performed to obtain important information such as the rate of return on investment and the payback period it would take to recover the cost of the initial investment. Lastly, a detailed hazard and operability analysis (HAZOP analysis) was performed over a section of the plant to prevent damage to personnel and equipment, and based on the analysis done, the project poses no threat to human life or damage to equipment. The data obtained from the economic analysis and the current situation caused by the COVID-19 virus both favor this project as a good investment. As the virus declines and the economy begins to boom, the demand for chief products that contain HFCS will begin to rise; ultimately increasing the demand for HFCS and making it easy to break into the market. In conclusion, this project was deemed safe and profitable, therefore, investment in this project is recommended.

*Very good report  
overall !!*





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## **12. APPENDIX**

### **12.1 Plant Design Basis**

#### Plant Capacity

Design Capacity: 706 MM lbs per year (1.5 MM metric tons)

Design Operating Time: 330 days per year

#### Raw Materials

Corn Starch (white solid powder), may form combustible dust concentrations in air

#### Product Glucose-Fructose Syrup Specifications

HFCS 42 & 55, clear viscous liquid, sweet odor, pH 5.9, melting/freezing point 146.1°C

#### Utility Specifications for Enzymatic Reactors

Thermostable  $\alpha$  - amylase, optimum pH of 6.5 at 105 °C

Glucoamylase, optimum pH of 4.5 at 60 °C

Immobilized glucose isomerase, optimum of pH 7.5 at 60 °C

#### Ambient Conditions

Maximum Temperature: 95 °F

Minimum Temperature: -10 °F

Relative Humidity: 25-95%

Maximum Windspeed: 30 mph



## 12.2 Sample Calculations

### 12.2.1 Example of Material Balance Calculation

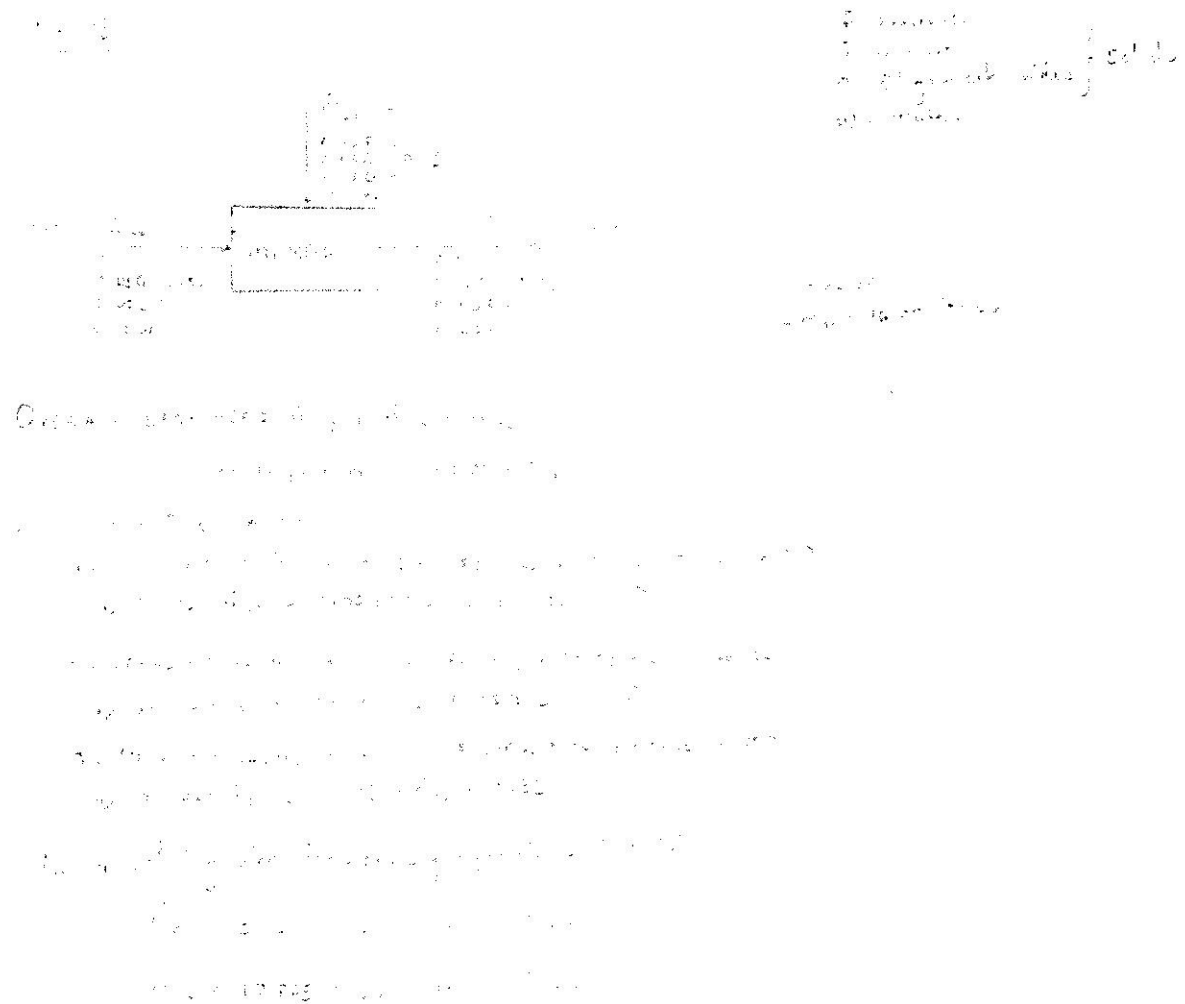


Figure 12.1 Example Material Balance Hand Calculation for Mixer 3





### 12.2.2 Example of Equipment Design Calculations

\* To find the heat duty required to heat the reactor, the overall heat transfer equation by combined conduction & convection is used

$$Q = \frac{T_1 - T_4}{\frac{1}{h_i A_i} + \frac{r_o - r_i}{k_r A_r} + \frac{1}{h_o A_o}} \quad \text{--- (1)}$$

$$Q = U_o A_o (T_1 - T_4) = U_o A_o \Delta T \quad \text{--- (2)}$$

\* To obtain  $h_i$  and  $h_o$  the eqn below is used

$$h = 1422 (1 + 0.0006 T(^{\circ}C)) \frac{V^{0.8}}{L^{0.2}}$$

The speed (V) of the heating fluid is obtained using Reynolds number formula for a Reynolds number  $\approx 2 \times 10^5$

$$h_i = 273 \text{ W/m}^2 \cdot K$$

$$h_o = 353 \text{ W/m}^2 \cdot K$$

\*  $k_r$  for stainless steel 316 =  $15 \text{ W/m}^2 \cdot K$

$$* A_{r,w} = \frac{A_o - A_i}{\ln(A_o/A_i)}$$

$$* T_1 = 60^{\circ}C = 140^{\circ}F$$

$$T_4 = 50^{\circ}C = 122^{\circ}F$$

$$\text{Finally ; } \boxed{Q = 10152 \text{ W} = 3463^{\circ} \text{ Btu/h}}$$

$$\boxed{U_o = U_o = 52 \text{ W/m}^2 \cdot K = 9.16 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^{\circ}F}$$



\* To obtain the pressure drop across the filter Ergun's equation is used

$$P = \frac{P_2}{P_0} = (1 - \alpha v)^{1/2}$$

where:  $\alpha = \frac{2 \beta_0}{A (1 - \phi) \rho_0^2}$  and  $\beta_0 = \frac{G / (1 - \phi)}{\rho_0 \phi_0 \phi^3} \left[ \frac{150 (1 - \phi) \mu}{D_p} + 1.75 G \right]$

$$G = P U = \frac{P \dot{V}_0}{A} = \left( 3170.3 \frac{\text{lb}}{\text{m}^3} \right) \left( \frac{22.44 \text{ m}^3/\text{hr}}{1.65 \text{ m}^2} \right) = 52723.05 \frac{\text{lb}}{\text{m}^2 \cdot \text{hr}}$$

$$\phi = 0.3$$

$$\mu = 1.8 \text{ cP} = 4.35 \text{ lbm}/24 \cdot \text{hr}$$

$$\rho_0 = 3170.3 \text{ lb}/\text{m}^3$$

$$D_p = 3 \text{ mm}$$

$$G_c = 4.17 \times 10^8 \frac{\text{lbm} \cdot \text{ft}}{\text{lb}_f \cdot \text{hr}^2}$$

$$P_0 = 4 \text{ atm}$$

Using all these information and solving;

$$\beta_0 = 9.029 \frac{\text{atm}}{\text{m}}$$

$$\alpha = 7.42 \times 10^{-6} \text{ lbm}^{-1}$$

$$P = 0.97$$

$$P_2 = 3.88$$

$$\Delta P = P_0 - P_2 = 0.12 \text{ atm} = 1.8 \text{ psi}$$



\* From headloss obtained for a PBR, an additional 3.2 ft is added to the bed height to obtain the vessel height

\* adding 1.5 ft to the top and bottom of the bed height

$$\text{Resulting vessel height} = 12.2 \text{ ft} \approx 19 \text{ ft}$$

\* Calculating the thickness to get the vessel diameter and volume

$$t = \frac{P_i d_i}{2\sigma(1 - P_f)} + C ; \quad \begin{aligned} P_i &= 0.10325 \text{ MPa} \\ d_i &= 1500 \text{ mm} \\ \sigma &= 136.637 \text{ MPa} \\ P_f &= 0.85 \\ C &= 7 \text{ mm} \end{aligned}$$

$$t = 8 \text{ mm} = 0.008 \text{ m} = 0.03 \text{ ft}$$

$$* \quad D_o = 2(0.03 \text{ ft}) + 4.2 \text{ ft} = 4.86 \text{ ft} \quad \text{outer diameter}$$

$$* \quad \text{Total volume} = \pi r_o^2 h = 477 \text{ ft}^3$$

Bed dimensions

$$V = 280 \text{ ft}^3$$

$$h = 15.28 \text{ ft}$$

$$D_i = 4.2 \text{ ft}$$

Vessel dimensions

$$V = 477 \text{ ft}^3$$

$$h = 19 \text{ ft}$$

$$D_o = 4.86 \text{ ft}$$

Starting with the design equation

$$\text{residence time } (\tau) = \frac{\text{Volume } (V)}{\text{volumetric flowrate } (Q_0)}$$

for a residence time of 4 hours and a volumetric flowrate of 7334 U.S. gal/hr ( $27.44 \text{ m}^3/\text{hr}$ )

$$V = 4 \text{ hours} \left( \frac{7334 \text{ U.S. gal/hr}}{1} \right) = 29,336 \text{ U.S. gal/hr}$$

$$V = 29,336 \text{ U.S. gal/hr} = 3220 \text{ ft}^3$$

According to a reference obtained from research, a plant producing 1000 tons/day of PEGS uses 20 reactors in parallel.

Our first design 14 reactors would be used; this would give a volume of  $220 \text{ ft}^3$  for one reactor

\* From literature, packed bed reactors usually have a  $\frac{L}{D}$  ratio of 0.5

$$V = \frac{\pi D^2 L}{4} \quad \text{where } L = 0.5D$$

$$\text{Solving } L = 15.25 \text{ ft}$$

$$D = 4.8 \text{ ft}$$

\* Therefore; for one reactor the bed dimensions are

$$\begin{array}{l} V = 220 \text{ ft}^3 \\ L = 15.25 \text{ ft} \\ D = 4.8 \text{ ft} \end{array}$$

} This is the volume  
occupied by the catalyst





### 12.3 Tables of Data Used

Table 12.1 Relative Sweetness of Sugars

| <b>Sugar or sweetener</b>       | <b>Relative sweetness</b> |
|---------------------------------|---------------------------|
| Sucrose                         | 1.0                       |
| Invert sugar                    | 0.85 - 1.0                |
| Fructose                        | 1.3                       |
| Glucose                         | 0.56                      |
| Galactose                       | 0.4-0.6                   |
| Maltose                         | 0.3-0.5                   |
| Lactose                         | 0.2-0.3                   |
| Xylitol                         | 1.01                      |
| Cyclamates                      | 30-80                     |
| Acesulfame K (Sunnette®)        | 200                       |
| Aspartame (Equal®, Nutrasweet®) | 100-200                   |
| Saccharin (The Pink Stuff)      | 200-300                   |
| Stevioside                      | 300                       |
| Sucralose (Splenda®)            | 600                       |
| Thaumatococin (Talin®)          | 2000-3000                 |

Source: Parker, Kay, et al. *Biotechnology and Molecular Biology Review*, Dec. 2010, pp. 71–78.

Table 12.2 Nutrition Values per 100g HFCS

| <b>Nutritional Items</b>      | <b>Value</b>        |
|-------------------------------|---------------------|
| Energy                        | 1,176 kJ (281 kcal) |
| Carbohydrates                 | 76 g                |
| Dietary fiber                 | 0 g                 |
| Fat                           | 0 g                 |
| Protein                       | 0 g                 |
| Water                         | 24 g                |
| Riboflavin (Vitamin B 2)      | 0.019 mg (1%)       |
| Niacin (Vitamin B3)           | 0 mg (0%)           |
| Pantothenic acid (Vitamin B5) | 0.011 mg (0%)       |
| Vitamin B6                    | 0.024 mg (2%)       |
| Folic acid (Vitamin B9)       | 0 µg (0%)           |
| Vitamin C                     | 0 mg (0%)           |
| Calcium                       | 6 mg (1%)           |
| Iron                          | 0.42 mg (3%)        |
| Magnesium                     | 2 mg (1%)           |
| Phosphorus                    | 4 mg (1%)           |
| Potassium                     | 0 mg (0%)           |
| Sodium                        | 2 mg (0%)           |
| Zinc                          | 0.22 mg (2%)        |

Source: Parker, Kay, et al. *Biotechnology and Molecular Biology Review*, Dec. 2010, pp. 71–78.

| <i>Calendar Year</i> | <i>Sugar<sup>a</sup></i> | <i>HFCS 42<sup>b</sup></i> | <i>HFCS 55<sup>b</sup></i> |
|----------------------|--------------------------|----------------------------|----------------------------|
| 2000                 | 42.41                    | 12.76                      | 15.72                      |
| 2001                 | 43.42                    | 13.66                      | 17.05                      |
| 2002                 | 43.10                    | 15.76                      | 18.50                      |
| 2003                 | 42.68                    | 16.38                      | 19.07                      |
| 2004                 | 42.64                    | 17.98                      | 20.54                      |
| 2005                 | 43.54                    | 18.62                      | 21.12                      |
| 2006                 | 49.58                    | 19.35                      | 21.77                      |
| 2007                 | 51.48                    | 23.41                      | 25.49                      |
| 2008                 | 52.91                    | 27.57                      | 29.32                      |
| 2009                 | 57.03                    | 31.51                      | 32.95                      |

<sup>a</sup> USDA 2010, Table 23.6—US retail refined sugar price, cents per pound

<sup>b</sup> USDA 2010, Table 23.9—US prices for high fructose corn syrup, wholesale list price, cents per pound dry weight

Figure 12.2 Relative Sugar Prices from 2010 United States Department of Agriculture (USDA) Report

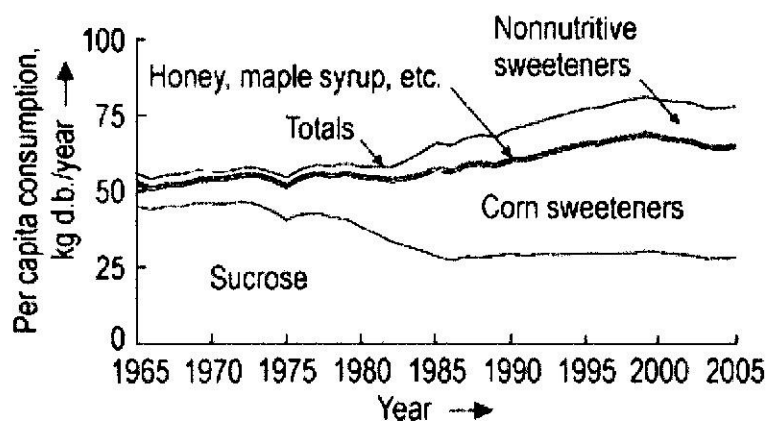


Figure 12.3 Consumption Trend of Various Syrups from Schenck, Fred W. *Ullmann's Encyclopedia of Industrial Chemistry*, 2006



**90 D.E. Corn**  
**(Sugar) Syrup**

| Commercial<br>Baume | Percent dry<br>Substance<br>by Wt. | Temperature °F   |                  |                  |                  |                  |
|---------------------|------------------------------------|------------------|------------------|------------------|------------------|------------------|
|                     |                                    | 40               | 80               | 120              | 160              | 200              |
|                     |                                    | <u>BTU/lb °F</u> | <u>BTU/lb °F</u> | <u>BTU/lb °F</u> | <u>BTU/lb °F</u> | <u>BTU/lb °F</u> |
| -1.0                | 0.0                                | 1.004            | .998             | .998             | 1.001            | 1.005            |
| 0.0                 | 1.8                                | 0.994            | .989             | .990             | .993             | .998             |
| 5.0                 | 10.8                               | .938             | .939             | .944             | .950             | .958             |
| 10.0                | 19.8                               | .881             | .889             | .898             | .908             | .919             |
| 15.0                | 29.0                               | .825             | .840             | .853             | .866             | .879             |
| 20.0                | 38.3                               | .770             | .790             | .807             | .822             | .837             |
| 25.0                | 47.7                               | .716             | .739             | .759             | .777             | .794             |
| 30.0                | 57.3                               | .662             | .689             | .712             | .732             | .750             |
| 32.0                | 61.2                               | .641             | .669             | .693             | .713             | .731             |
| 34.0                | 65.2                               | .620             | .649             | .674             | .694             | .713             |
| 36.0                | 69.2                               | .600             | .630             | .655             | .675             | .694             |
| 38.0                | 73.2                               | .582             | .611             | .635             | .657             | .675             |
| 40.0                | 77.3                               | .564             | .593             | .617             | .638             | .655             |
| 41.0                | 79.4                               | .556             | .583             | .607             | .628             | .646             |
| 42.0                | 81.5                               | .547             | .574             | .598             | .618             | .636             |
| 43.0                | 83.6                               | .539             | .565             | .588             | .607             | .625             |
| 44.0                | 85.7                               | .532             | .556             | .578             | .597             | .615             |
| 45.0                | 87.8                               | .525             | .548             | .568             | .587             | .604             |
| 46.0                | 89.9                               | .517             | .539             | .558             | .577             | .594             |

Figure 12.4 90 DE Corn Syrup Heat Capacity from Corn Refiners Association, Inc., 2018

## 12.4 Product Information Sheet

Product Information



### DOWEX™ MONOSPHERE™ 77

Ion Exchange Resin for Sweetener Applications

| Product               | Type            | Matrix                   | Functional group |
|-----------------------|-----------------|--------------------------|------------------|
| DOWEX™ MONOSPHERE™ 77 | Weak base anion | Styrene-DVB, macroporous | Tertiary amine   |

#### Typical Physical and Chemical Properties

|                             |                     |                |
|-----------------------------|---------------------|----------------|
| Ionic form as produced      |                     | FB (free base) |
| Total exchange capacity,    | eq/L                | 1.7            |
| min. Weak base capacity,    | eq/L                | 1.5            |
| min.                        |                     |                |
| Water content               | %                   | 40 - 50        |
| Bead size distribution      |                     |                |
| Volume median diameter      | µm                  | 475 - 600      |
| Total swelling (FB → HCl)   | %                   | 22             |
| Whole uncracked beads, min. | %                   | 95             |
| Particle density            | g/mL                | 1.04           |
| Shipping weight**           | g/L                 | 640            |
|                             | lbs/ft <sup>3</sup> | 40             |

60°C (140°F)

#### Recommended

0 - 7

#### Operating • Conditions

- Maximum operating temperature 91 cm (3 ft)
- (H<sup>+</sup> form) pH range Bed depth, min.
- Flow rates:
  - Service 2 - 4 bed volumes/hour See Figure 1 30 - 45 min.
  - Backwash 30 - 45 min.
  - Regeneration time 2 - 10 bed volumes /hour
  - Displacement rinse
  - Fast rinse (if applicable)
- Total rinse requirement 3 - 5 bed volumes



| Regenerants                     | NaOH <sup>†</sup> | Na <sub>2</sub> CO <sub>3</sub> | NH <sub>4</sub> OH |
|---------------------------------|-------------------|---------------------------------|--------------------|
| Concentration (%)               | 4                 | 5                               | 5                  |
| Level, 100% basis <sup>††</sup> |                   |                                 |                    |
| lbs/ft <sup>3</sup>             | 4 - 5             | 6 - 7                           | 4 - 5              |
| kg/m <sup>3</sup>               | 64 - 80           | 96 - 112                        | 64 - 80            |
| Temperature, max.               | 60°C (140°F)      | 60°C (140°F)                    | 60°C (140°F)       |

<sup>†</sup> Recommended

<sup>††</sup> Regeneration level may be lower for counter-current regeneration systems.

<sup>\*\*</sup> As per the backwashed and settled density of the resin, determined by ASTM D-2187.

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<sup>™®</sup> Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow Form No. 177-

**Typical Properties** DOWEX<sup>™</sup> MONOSPHERE<sup>™</sup> 77 resin is the newest in the DOWEX line of weak base anion **and Applications** resins made using a Dow-patented process which produces beads with remarkable size

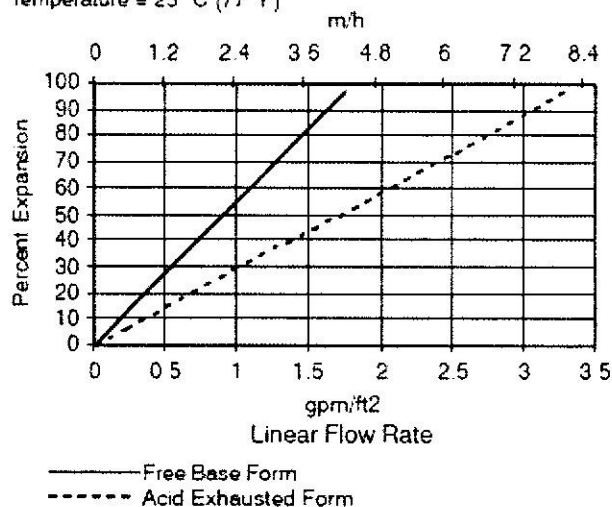
uniformity. Chemically & physically optimized for syrup processing,  
DOWEX

MONOSPHERE 77 provides an improved balance of high operating capacity, excellent physical strength, economical regeneration, long resin life and low operating costs.

**Packaging** 25 liter bags, 5 cubic feet fiber drums or 1 cubic meter super sacks.

**Figure 1. Backwash Expansion Data**

Temperature = 25° C (77° F)



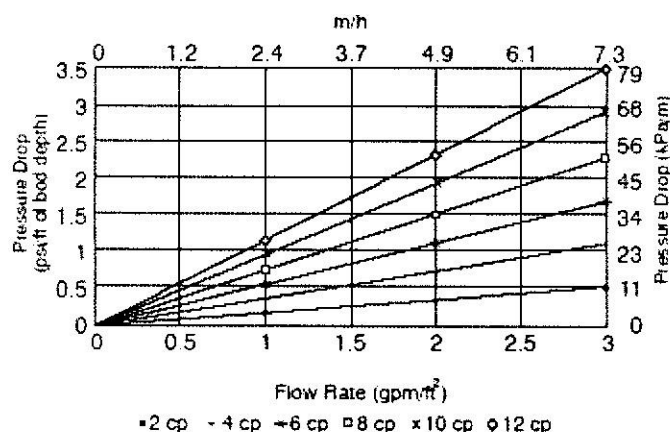
**For other temperatures use:**

$$F_T = F_{77^\circ F} [1 + 0.008 (T_F - 77)], \text{ where } F \equiv \text{gpm/ft}^2$$

$$F_T = F_{25^\circ C} [1 + 0.008 (1.8 T_C - 45)], \text{ where } F \equiv \text{m/h}$$

**Figure 2. Pressure Drop Data**

Temperature = 20° C (68° F)



**For other temperatures use:**

$$P_T = P_{20^\circ C} / (0.026 T_C + 0.48), \text{ where } P \equiv \text{bar/m}$$

$$P_T = P_{68^\circ F} / (0.014 T_F + 0.05), \text{ where } P \equiv \text{psi/ft}$$

### DOWEX™ Ion Exchange Resins

For more information about DOWEX resins, call the Dow Water Solutions business:

North America: 1-800-447-4369  
 Latin America: (+55) 11-5188-9222  
 Europe: (+32) 3-450-2240  
 Pacific: +60 3 7958 3392  
 Japan: +813 5460 2100 China: +86 21 2301 9000

<http://www.dowwatersolutions.com>

Warning: Oxidizing agents such as nitric acid attack organic ion exchange resins under certain conditions. This could lead to anything from slight resin degradation to a violent exothermic reaction (explosion). Before using strong oxidizing agents, consult sources knowledgeable in handling such materials.

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*Lenntech*

## **DOWEX™ MONOSPHERE™ 88**

Ion Exchange Resin for Sweetener Applications

| Product               | Type               | Matrix                      | Functional group |
|-----------------------|--------------------|-----------------------------|------------------|
| DOWEX™ MONOSPHERE™ 88 | Strong acid cation | Styrene-DVB,<br>macroporous | Sulfonate        |

### **Typical Physical and Chemical Properties**

|                                                    |                            |                 |
|----------------------------------------------------|----------------------------|-----------------|
| Ionic form as produced                             |                            | Na <sup>+</sup> |
| Total exchange capacity, min.                      | eq/L                       | 1.8             |
| Water content                                      | %                          | 42 - 50         |
| Bead size distribution                             |                            |                 |
| Volume median                                      |                            | 500 - 600       |
| diameter 400 - 720 µm,<br>min.                     | µm<br>%                    | 95              |
| Total swelling (Na <sup>+</sup> → H <sup>+</sup> ) | %                          | 5               |
| Whole uncracked beads, min.                        | %                          | 95              |
| Particle density                                   | g/mL                       | 1.2             |
| Shipping weight**                                  | g/L<br>lbs/ft <sup>3</sup> | 800<br>50       |

|                             |                                                       |                          |
|-----------------------------|-------------------------------------------------------|--------------------------|
| <b>Recommended</b>          | • Maximum operating temperature (H <sup>+</sup> form) | 93°C (200°F)             |
| <b>Operating Conditions</b> | • pH range                                            | 0 - 14                   |
|                             | • Bed depth, min.                                     | 91 cm (3 ft)             |
|                             | • Flow rates:                                         |                          |
|                             | Service                                               | 2 - 4 bed volumes/hour   |
|                             | Backwash                                              | See Figure 1             |
|                             | Regeneration time                                     | 30 - 45 min.             |
|                             | Displacement rinse                                    | 30 - 45 min.             |
|                             | Fast rinse (if applicable)                            | 2 - 10 bed volumes /hour |

- Total rinse requirement                      2 - 5  
bed volumes
- Regenerant:
 

|                                |                                                        |
|--------------------------------|--------------------------------------------------------|
| Concentration                  | 7% HCl                                                 |
| Level, 100% basis <sup>†</sup> | 5 - 6 lbs/ft <sup>3</sup><br>80 - 96 kg/m <sup>3</sup> |
| Temperature, max.              | 93°C (200°F)                                           |

<sup>†</sup> Regeneration level may be lower for counter-current regeneration systems.

\*\* As per the backwashed and settled density of the resin, determined by ASTM D-2187.

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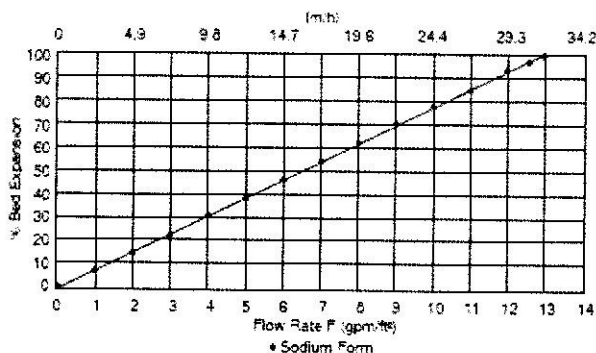
™® Trademark of The Dow Chemical Company ("Dow") or an affiliated company of Dow    Form No. 177-

**Typical Properties** DOWEX™ MONOSPHERE™ 88 resin is a strong acid cation resin made using a Dow and **Applications** patented process which produces beads with remarkable size uniformity. Chemically optimized for syrup processing, they provide an ideal balance of high operating capacity, excellent physical strength, economical regeneration, long resin life and low operating costs.

**Packaging**                      25 liter bags, 5 cubic feet fiber drums or 1 cubic meter super sacks.



**Figure 1. Backwash Expansion Data**

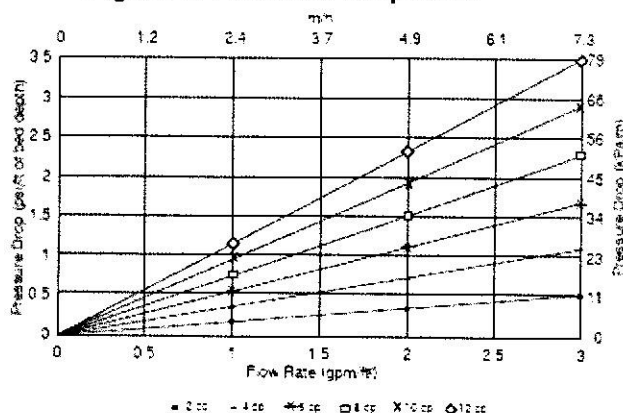


**For other temperatures use:**

$$F_T = F_{77^\circ\text{F}} [1 + 0.008 (T_F - 77)], \text{ where } F \equiv \text{gpm/ft}^2$$

$$F_T = F_{25^\circ\text{C}} [1 + 0.008 (1.8T_C - 45)], \text{ where } F \equiv \text{m/h}$$

**Figure 2. Pressure Drop Data**



**For other temperatures use:**

$$P_T = P_{20^\circ\text{C}} / (0.026 T_C + 0.48), \text{ where } P \equiv \text{bar/m}$$

$$P_T = P_{68^\circ\text{F}} / (0.014 T_F + 0.05), \text{ where } P \equiv \text{psi/ft}$$

**Warning:** Oxidizing agents such as nitric acid attack organic ion exchange resins under certain conditions. This could lead to anything from slight resin degradation to a violent exothermic reaction (explosion). Before using strong oxidizing agents, consult sources knowledgeable in handling such materials.

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## DOWEX™ MONOSPHERE™ 99 Ca/320

Separation Resin for Chromatographic Separations (Primarily Sugars and Sugar Alcohols)

| Product                      | Type               | Matrix           | Functional group |
|------------------------------|--------------------|------------------|------------------|
| DOWEX™ MONOSPHERE™ 99 Ca/320 | Strong acid cation | Styrene-DVB, gel | Sulfonate        |

### Typical Physical and Chemical Properties

|                                 |     |                     |                               |
|---------------------------------|-----|---------------------|-------------------------------|
| Ionic form as delivered         |     |                     | Ca++                          |
| Total capacity, min.            |     | eq/L                | 1.5 (H <sup>+</sup> form)     |
| Water content                   |     | %                   | 57 - 61 (H <sup>+</sup> form) |
| Whole uncracked beads, min.     |     | %                   | 98                            |
| Particle density                |     | g/mL                | 1.27                          |
| Apparent bulk density:**        |     |                     |                               |
| Backwashed, settled and drained | g/L | lbs/ft <sup>3</sup> | 770 - 820                     |
| Tapped and settled              |     | g/L                 | 48 - 51                       |
|                                 |     | lbs/ft <sup>3</sup> | 785 - 850                     |
|                                 |     |                     | 49 - 53                       |

### Bead Size Distribution (Light Obscuration Instrument Particle Size)

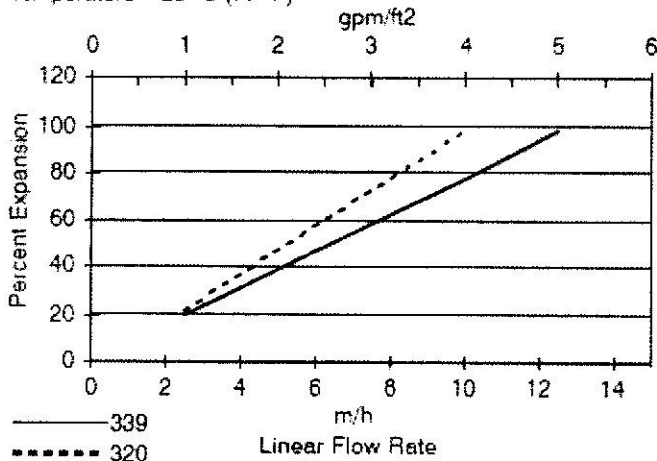
|                        |          | Microns   |
|------------------------|----------|-----------|
| Volume median diameter |          | 300 - 330 |
| Broad range            | min. 90% | 285 - 350 |
| Narrow range           | min. 75% | 300 - 335 |
| Fine fines             | max. 1%  | < 260     |
| Coarse fines           | max. 4%  | < 280     |
| Fine coarse            | max. 4%  | > 380     |
| Coarse coarse          | max. 1%  | > 450     |

\*\* As per the backwashed and settled density of the resin, determined by ASTM D-2187.



**Figure 1. Backwash Expansion Data**

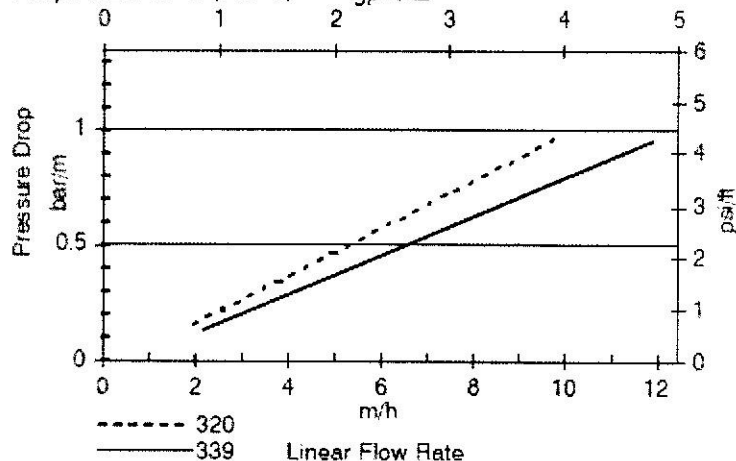
Temperature = 25° C (77° F)



**Figure 2. Pressure Drop Data**

**PRESSURE DROP - 42% Fructose @ 50% DS**

Temperature 60° C (140° F)



**For other temperatures use:**

$$F_T = F_{77°F} [1 + 0.008 (T_F - 77)], \text{ where } F \equiv \text{gpm/ft}^2$$

$$F_T = F_{25°C} [1 + 0.008 (1.8T_C - 45)], \text{ where } F \equiv \text{m/h}$$

**DOWEX™ Ion Exchange Resins**

For more information about

DOWEX resins, call the Dow Water Solutions business:

North America: 1-800-447-4369

Latin America: (+55) 11-5188-9222

Europe: (+32) 3-450-2240

Pacific: +60 3 7958 3392

Japan: +813 5460 2100 China:

+86 21 2301 9000

<http://www.dowwatersolutions.com>

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**DOWEX™ OPTIPORE™ SD-2 Adsorbent**

Polymeric Adsorbent for Sucrose and Other Sweetener Applications

**Applications**  
surface area

DOWEX™ OPTIPORE™ SD-2 adsorbent is an adsorbent with a high specific

and high porosity which shows exceptional mechanical, thermal and chemical stability. It is specially designed for decolorization as well as taste and odor removal in sweetener applications and complies with the U.S. Food, Drug and Cosmetic Act as amended under Food Additive Regulation 21 CFR 173.25.

This adsorbent has similar pore size distribution and adsorption properties to activated carbon so that it can be used as a direct replacement for carbon in many sweeteners applications. DOWEX OPTIPORE SD-2 has the additional advantage of containing macropores which improve the bulk movement of solutions in and out of the bead. The resulting improvement in kinetics leads to faster production flow rates and smaller beds.

The adsorbent is lightly functionalized with weak base groups to provide a hydrophilic character giving the adsorbent good wettability and compatibility with acid and base regenerants. Regeneration requires only dilute caustic, dilute acid, and hot water.

More detailed information on the use of DOWEX OPTIPORE SD-2 adsorbent in your particular application can be obtained from your Dow technical contact or from your Dow sales representative.

**Product Specifications**

| Product                       | Type      | Matrix                                       | Functional group |
|-------------------------------|-----------|----------------------------------------------|------------------|
| DOWEX OPTIPORE SD-2 Adsorbent | Adsorbent | Macroporous styrene-divinylbenzene copolymer | Tertiary amine   |

**General Properties**

|                       |                       |
|-----------------------|-----------------------|
| Dry weight capacity   | 0.8 meq/g             |
| Typical surface area  | 800 m <sup>2</sup> /g |
| Average pore diameter | 50 Angstrom           |



|                             |                                  |
|-----------------------------|----------------------------------|
| Water content (%)           | 50 - 62                          |
| Particle size:              |                                  |
| > 1,190 $\mu\text{m}$       | $\leq 2\%$                       |
| < 297 $\mu\text{m}$ (total) | $\leq 3\%$                       |
| < 210 $\mu\text{m}$         | 0.3% max.                        |
| < 105 $\mu\text{m}$         | 0.0% max.                        |
|                             | 5%                               |
|                             | 90%                              |
| Density                     | 1.04 g/mL                        |
| Shipping weight**           | 670 g/L (42 lb/ft <sup>3</sup> ) |

\*\* As per the backwashed and settled density of the resin, determined by ASTM D-2187.

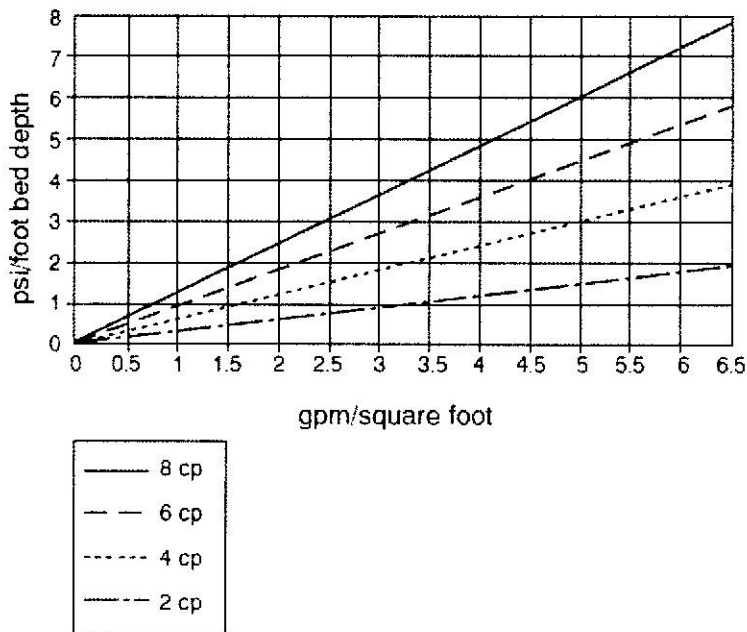
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### Typical Operating Condition Ranges (dependent on application)

|                                 |                                             |
|---------------------------------|---------------------------------------------|
| Operating temperature           | 50 - 85°C                                   |
| Operating pH                    | 3 - 8.5                                     |
| Service/regeneration flow rates | 2 - 6 BV/hr                                 |
| Regenerant type                 | NaOH, HCl or H <sub>2</sub> SO <sub>4</sub> |

**Figure 1. Pressure Drop**



[11] Patent number: 4,950,332  
[45] Date of patent: August 21, 1990

**[57] Abstract**

A process for decolorizing an aqueous sugar solution by contacting the solution with an absorbent resin, wherein the adsorbent resin is a macroporous copolymer being post-crosslinked in a swollen state in the presence of a Friedel-Crafts catalyst and functionalized with hydrophilic groups prior to contact with aqueous sugar solution.

**[75] Inventors**

Richard T. Springfield, H. Robert Goltz, Seth I. Norman, Upen J. Bharwada, Robert L LaBrie, all of Midland, Mich.

**[73] Assignee**

The Dow Chemical Company – Midland, Mich.

**DOWEX™ Ion Exchange Resins**

**For more information about**

**DOWEX resins, call the Dow Water Solutions business:**

North America: 1-800-447-4369

Latin America: (+55) 11-5188-9222

Europe: (+32) 3-450-2240

Pacific: +60 3 7958 3392

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+86 21 2301 9000

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