Preliminary Design for Cellulosic Ethanol Production Facility Capable of Producing 50 MMgal/yr

The goal of this project was to develop a complete preliminary design for a cellulosic ethanol facility with a capacity of 50 MMgal/yr of ethanol.

The main components of the facility were first approximated by scaling down the design prepared by the National Renewable Energy Laboratory for a 70 MMgal/yr cellulosic ethanol facility [1]. While preparing the preliminary design for this process a better understanding of the requirements for the facility was developed, allowing for the enhancement of detail for the saccharification, fermentation, and separations sections. Pre-treatment design was solely based upon required residence times.

Corn stover was initially considered as the raw material of choice, as requested by the Client; although, attention was given to incorporating another possible feedstock (wheat straw). Central location of the plant to the raw material, while balancing the factors involving product transportation, was to be optimized. An analysis of the environmental impact of removing corn stover from fields to use as a feedstock was also requested to be included in the completed design.

A final economic analysis of the cellulosic facility was to be based upon as 12% after-tax rate of return over 20 years, with 5-year MACRS depreciation. Working capital was to be assumed to be 50% of the first-year cost of manufacturing without depreciation (COM_d), with zero salvage value. Any available subsidies offered by the government were also to be included in the economic analysis. Cases including and not including the subsidies were requested to be presented in the final deliverable.

Results

A block flow diagram for the overall process is given in Figure 1. A brief description of the important processes is given below.

Feed Handling: Figure 2

The corn stover or wheat straw is taken from storage, washed, and shredded. The wash water is condensate from the separations section (Unit A400). The used wash water is sent to a clarifier and the remaining solids are disposed. A portion of the used wash water is sent back to a storage tank for reuse.

Pretreatment and Conditioning: Figure 3

The feedstock is then steamed and reacted in the acid hydrolysis reactor trains. Afterwards, the product is sent to the blowdown tank to remove the solids and liquid components. The resulting slurry is then sent to solid/liquid separations where the excess acid is neutralized and the gypsum is removed. The hydrolyzate is then sent to saccharification and fermentation (Unit A300).

Saccharification and Fermentation: Figure 4

In this block, the hydrolyzate is reacted with bacteria grown in the seed train reactors. The resulting ethanol mixture is sent to separations for distillation and the waste gas is sent to the scrubber in the same section.

Separations

In this section, the ethanol is distilled in the rectification section (Figure 5), purified of excess water in the dehydration (Figure 6) and evaporation sections

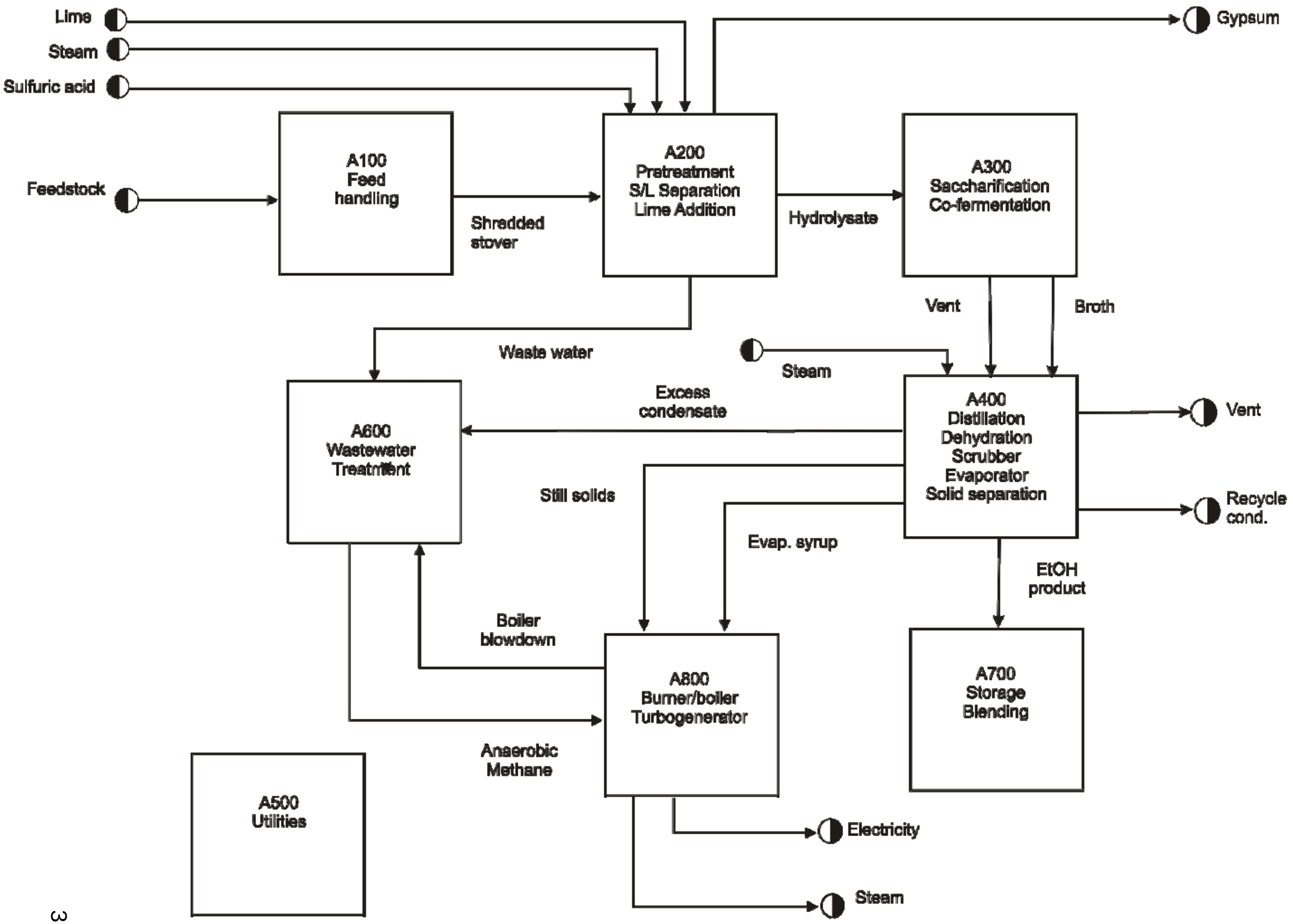


Figure 1: Cellulosic Ehtanol Process

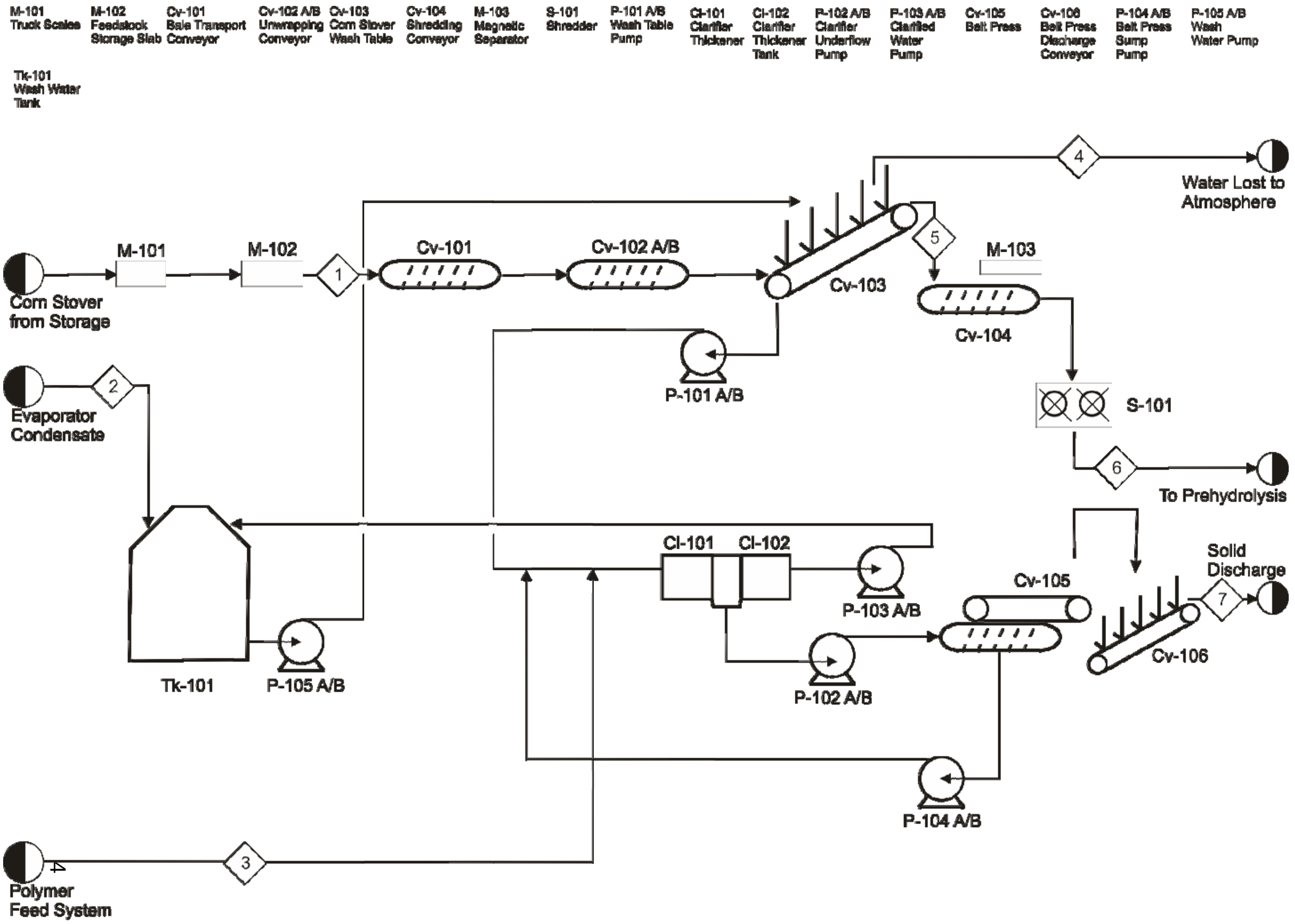


Figure 2: Feed Handling

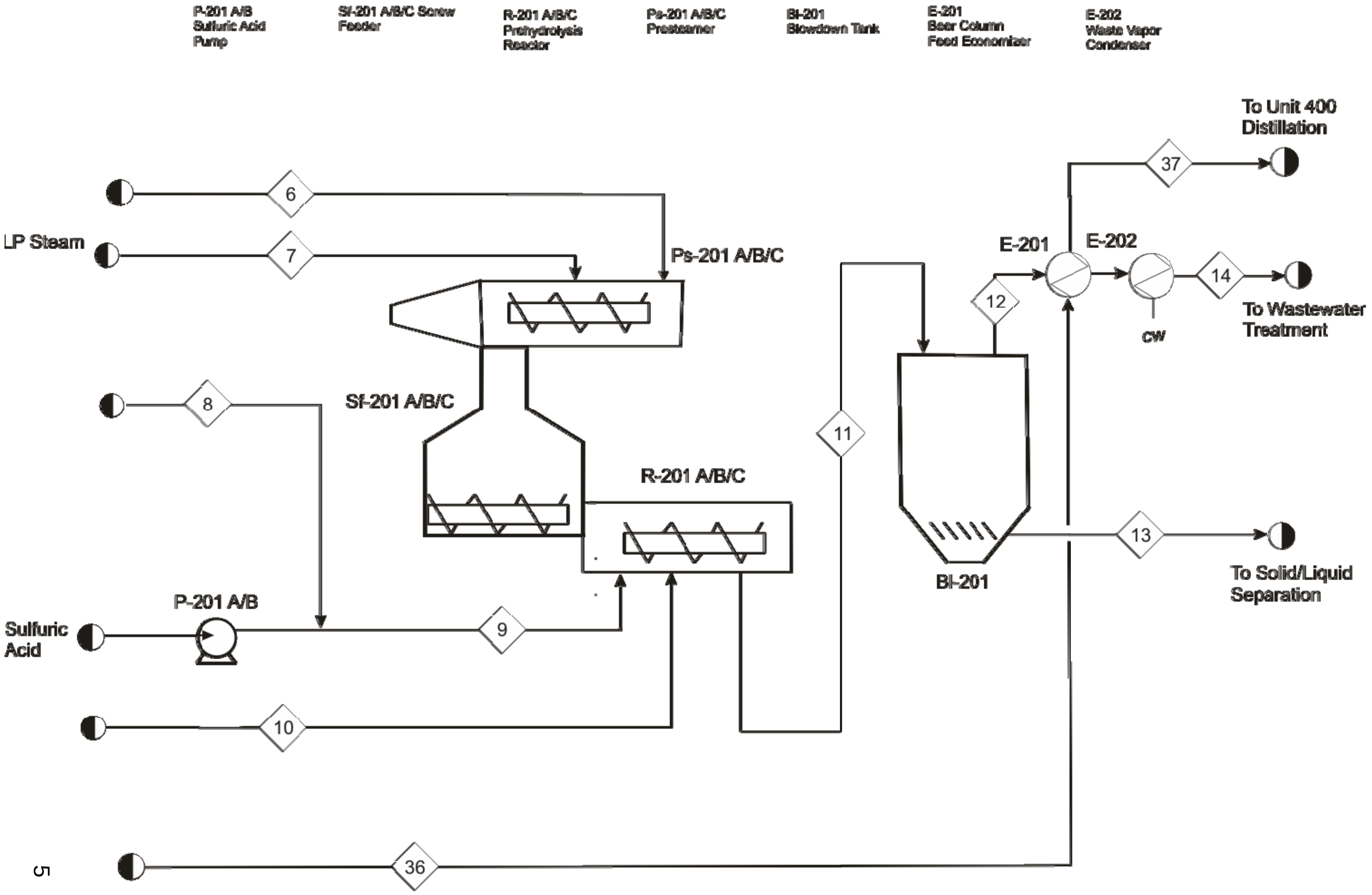


Figure 3: Pretreatment and Conditioning

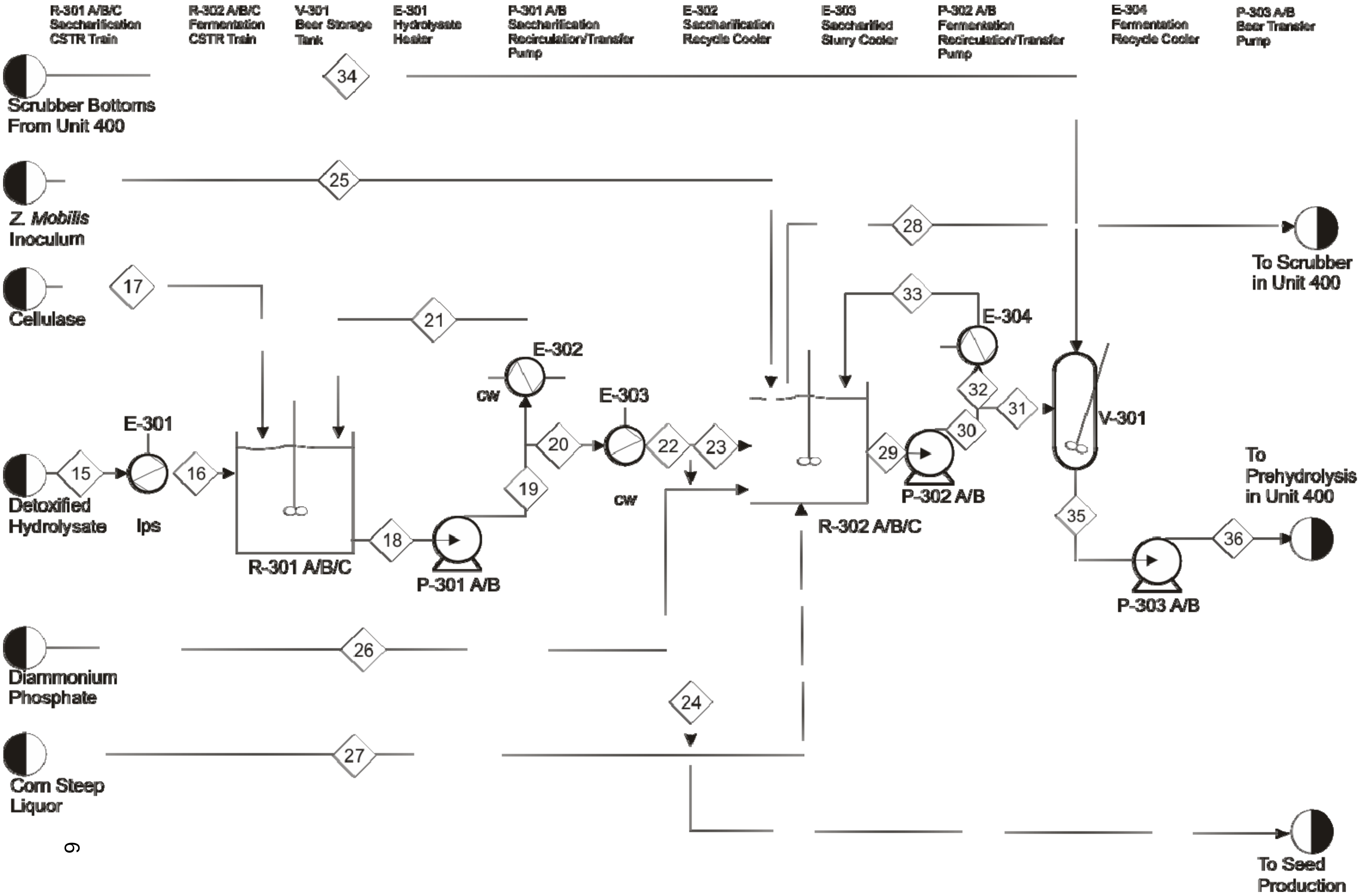


Figure 4: Saccharification & Co-fermentation

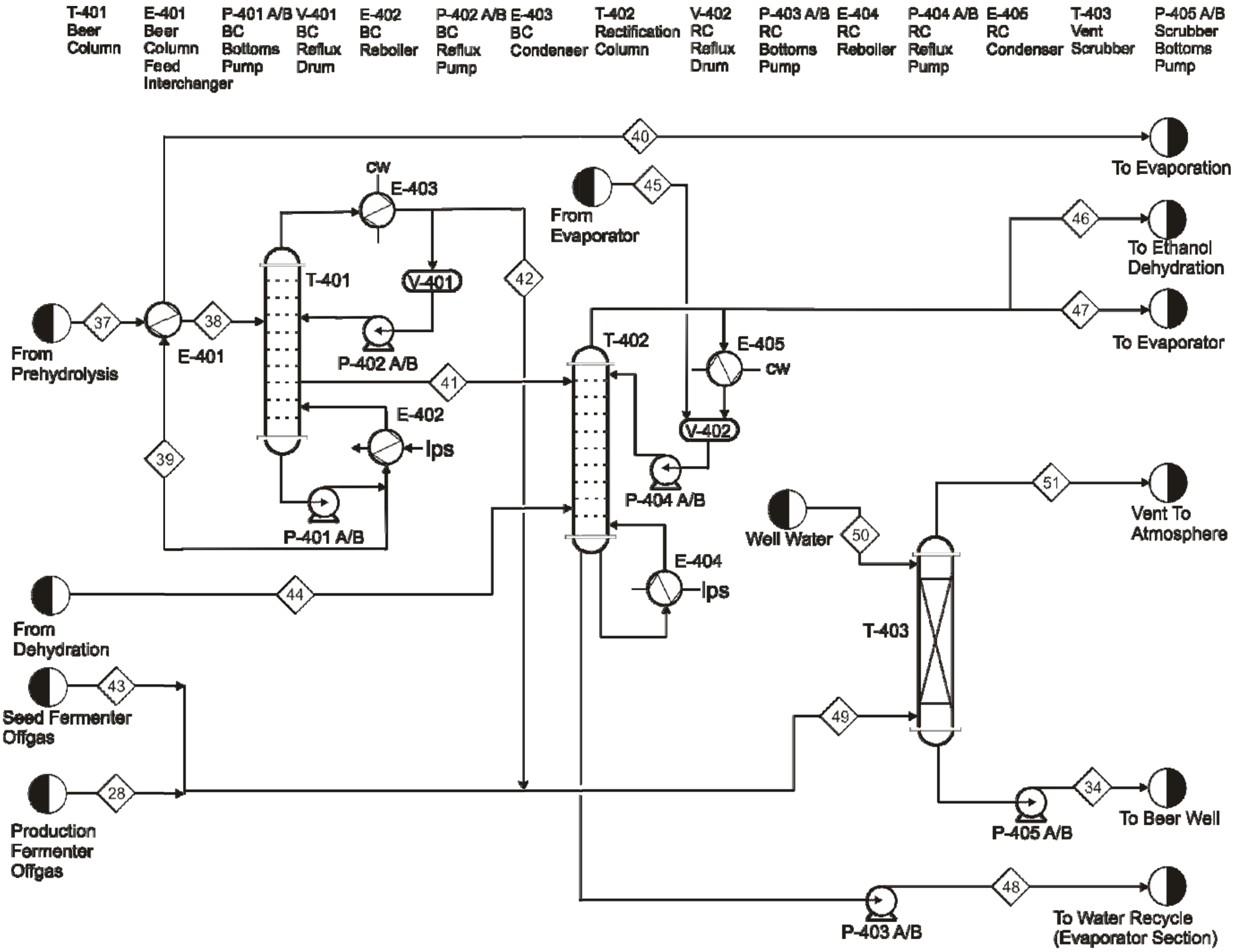


Figure 5: Rectification

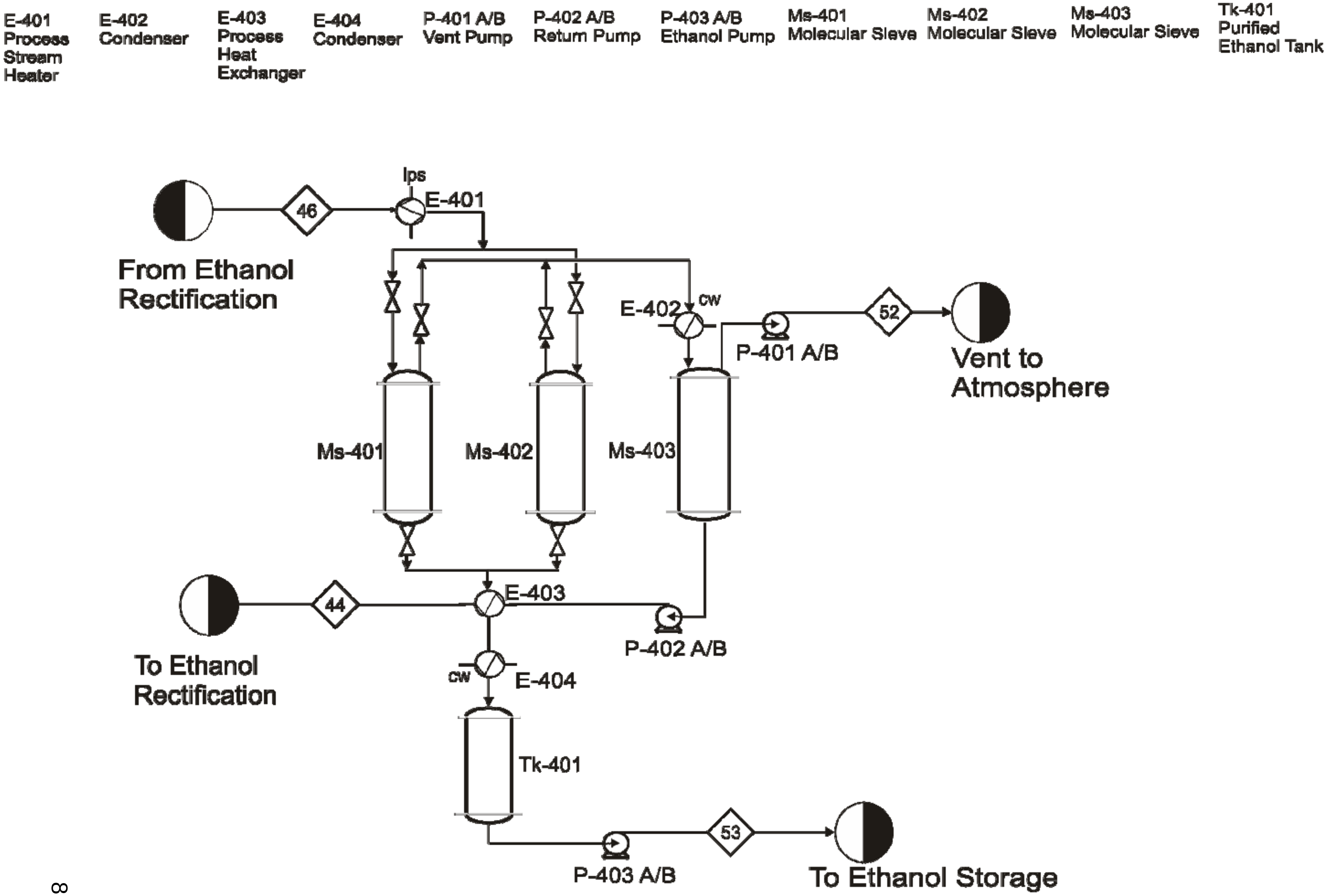


Figure 6: Dehydration

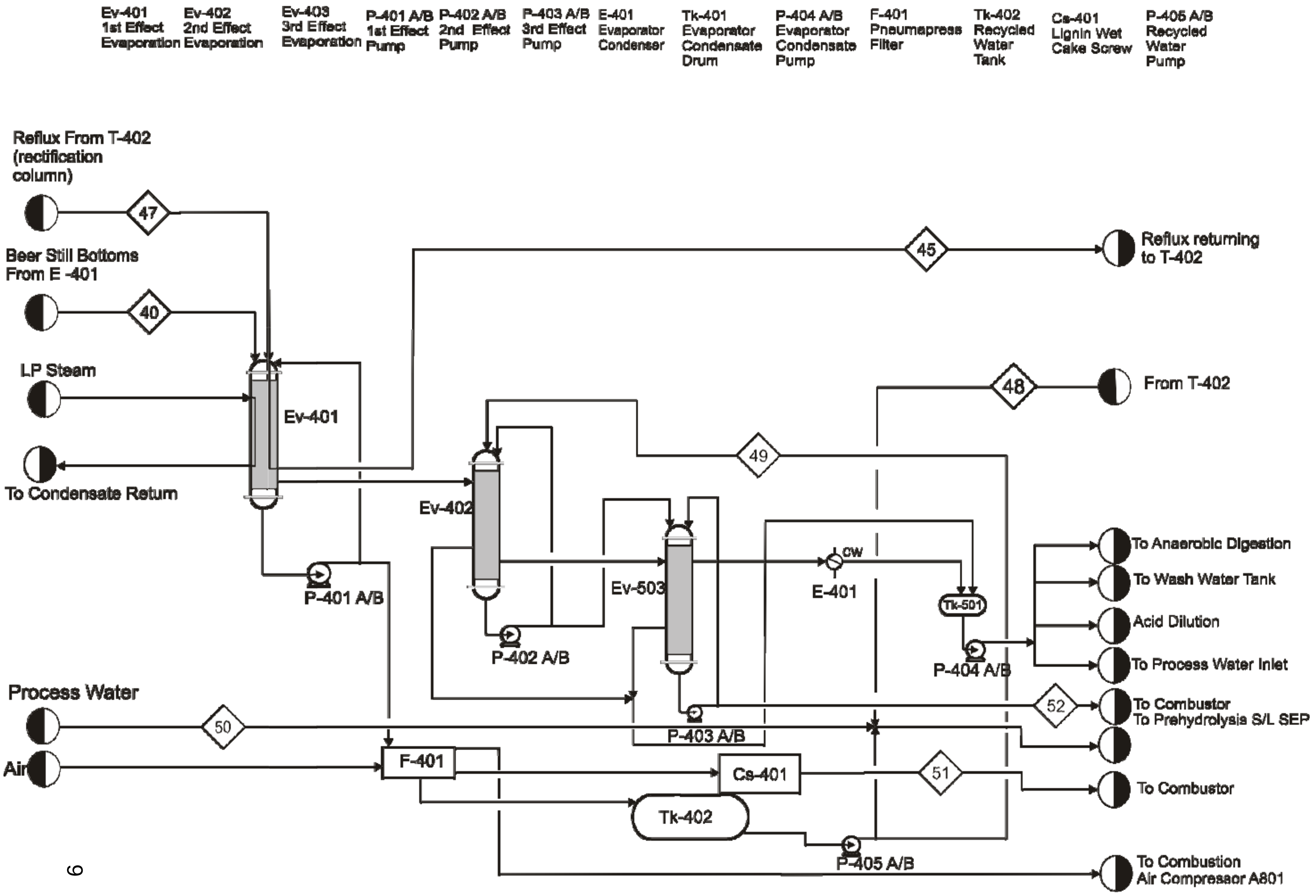


Figure 7: Evaporation

(Figure 7), and sent to storage/blending (Unit A700). The solids are removed from the slurry and sent to the boiler to be combusted and the waste gases are sent through the scrubber. Excess condensate is sent to wastewater treatment (Unit A600).

Storage

Here, the ethanol is blended with gasoline and stored. Some corn steep liquor is fed into the process to aid in bacteria production. This is also the location where purchased enzyme and sulfuric acid are stored and pumped to their respective destinations.

Burner/Boiler Turbogenerator

Here, methane gas from wastewater treatment, leftover syrup, and solids from separations are combusted to produce process steam and electricity. The blowdown steam from the turbine is sent to wastewater treatment.

Wastwater Treatment

Here, wastewater and excess condensate are combined with nutrients and put through aerobic and anaerobic digestion. Carbon dioxide and other waste gases are vented to the atmosphere and the treated water is sent to utilities (Unit A900) to be recycled.

Utilities

Treated wastewater is collected here to be sterilized and recycled. Air is also dried here before being put into the process.

Economics

Table 1 shows the important results of the economic analysis.

Table 1: Economic Analysis

	Base Case Electricity & No Subsidies	Best Case Electricity & Subsidies	No Electricity & No Subsidies	No Electricity & Subsidies
DCFROR	9.46%	16.74%	5.48%	14.46%
DPP	19 yr	6.1 yr	NA	6.8
NPV (millions of $)	-22.55	46.77	-48.51	20.81
FCI_L (millions of $)	145.8	145.8	118.0	118.0
COM_d (millions of $)	59.6	59.6	70.8	70.8
Minimum Ethanol Price ($/gal)	1.722	NA	1.862	NA
% of Monte Carlo Scenarios giving a DCFROR > 12%	63.2	99.1	37.5	98.5

*DPP = Discounted Payback Period
** Best case based on probability of making the most profit

A basic layout for the storage lots is shown in Figure 8. This figure illustrates the general arrangement of storage lots situated around the facility. The facility will be built near a rail road. The facility has four equally sized storage lots for feed stock. The general arrangement of bales in these lots is also shown.

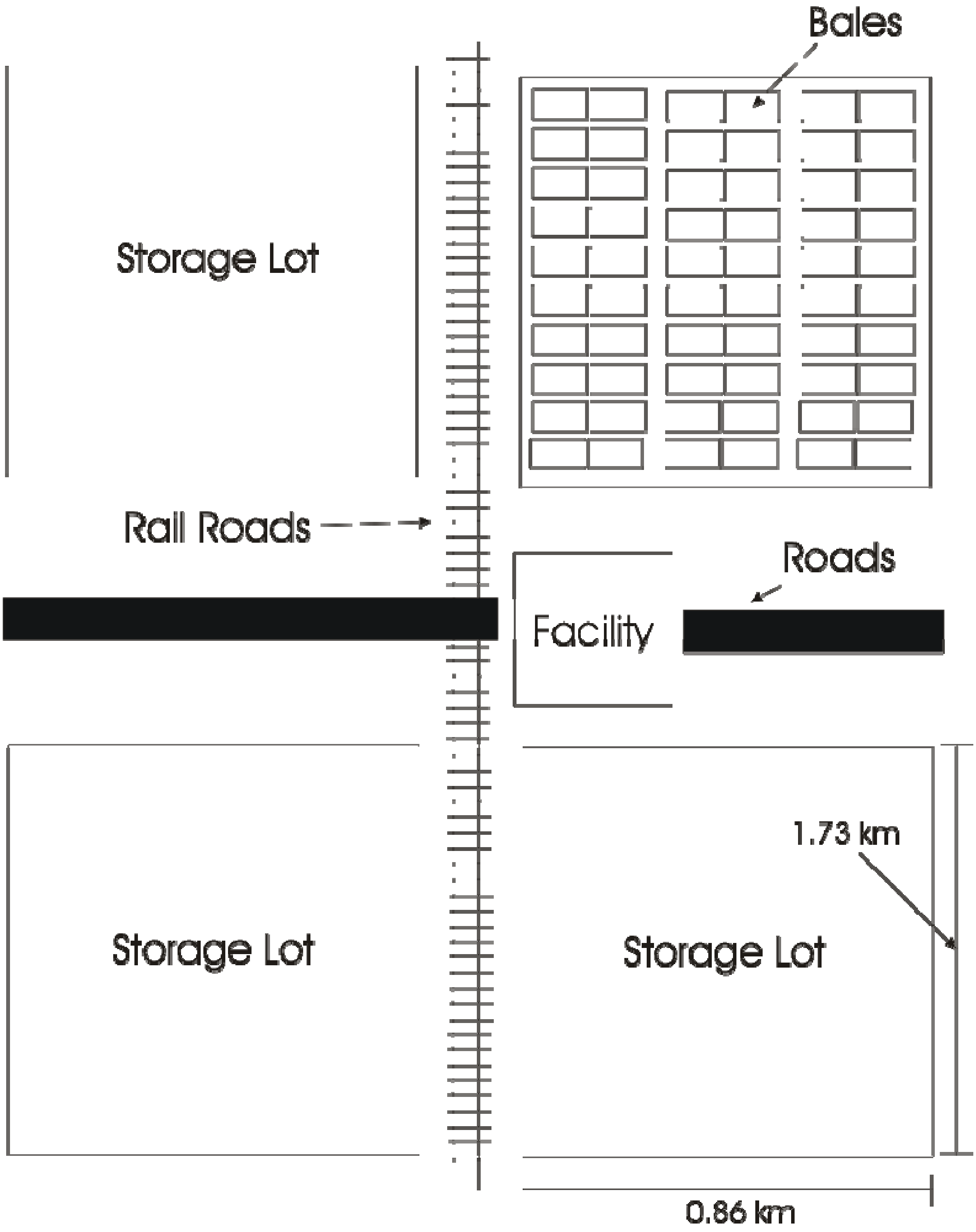


Figure 8: Layout of Storage Lots in Relation to Facility (Not to Scale)

Fermentation Section and Mathematical Model

It was necessary to find an accurate mathematical model for the conversion of xylose and glucose to ethanol using the bacterium, *Zymomonas mobilis*, as well as a continuous method of production. These bacteria are produced onsite to be fed into the fermentor. The bacteria are produced in a five-tank seed train in order to simulate a continuous process. This ensures a continuous stream of inoculate is available for fermentation.

After conducting research on the bacterium, a model specific to this problem was found [2]. This model was tested for accuracy by using a computer algebra system. The results from the simulation were compared to experimental data recorded for the same bacterium [3].

The model correlated with the experimental data fairly well. However, there was room for improvement. The model predicted glucose consumption and conversion into ethanol and biomass very well but deviated significantly for predictions of xylose consumption and conversion. In order to correct this, the model parameters were examined. After determining which parameters had the most effect on the model's predictions, a multivariable optimization was conducted to match the experimental data more closely. A more accurate model was generated by changing parameters associated with xylose metabolism including biomass growth rate while feeding on xylose, the specific substrate utilization rate, the specific ethanol production rate, the substrate inhibition constant, and the maximum ethanol concentration. Graphical illustrations of the model before and after optimization as well as the mathematical model used can be found in Appendix A: Fermentation Model.

Glucose and xylose concentrations were then optimized for the model to produce the highest concentration of ethanol over the shorter time period. By a trial-and-error method, the most productive concentrations for glucose and xylose were found to be 164.3 g/L and 42.9 g/L, respectively. This yielded approximately 70.5 g/L of ethanol at 95% yield. This conversion was chosen due to the asymptotic nature of the ethanol production model. The residence time for this yield was close to 24 hours. To increase the yield, significantly longer residence times were required. This increased the size and number of reaction tanks required for the process.

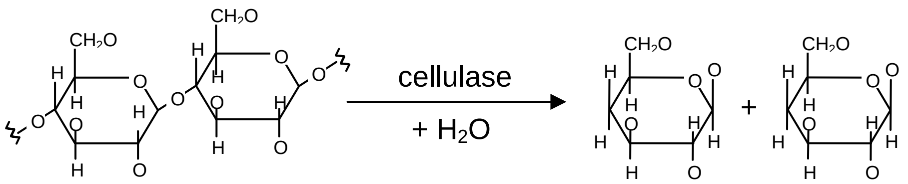
The chemical compositions of corn stover and wheat straw were used to determine the required feedstock flow rate to reach the target production quota of 50 million gallons per year [4]. It was determined that approximately 2,725 tonne of feed stock were required per day to reach the desired capacity.

Wheat straw was used to determine the required reaction tank sizes due to the higher concentration of hemi-cellulose in it compared to corn stover. A longer time is required for wheat straw because the extra hemi-cellulose and subsequently produced xylose take longer to ferment. The fermentation volume required was calculated based on the total volume of 24 hours worth of reactor feed. The reactor feed's volume was based on the amount of water required to reach the target glucose and xylose concentrations for the 2725 tonne per day feedstock flow rate. It was determined that roughly 1.8 million gallons of reaction volume would be required to hold the fermentation mixture for the required residence time.

The most economical configuration for the fermentation reaction consisted of a single large tank with agitators for power. However, it was decided to split the volume into two equally sized tanks to help ensure that enough agitation power was supplied per unit volume to maintain a well-mixed system. A larger agitator in the single tank could have supplied the required power, but the higher shear rate could have damaged the bacteria needed for fermentation.

Saccharification

The saccharification section of the facility decomposes cellulose into glucose. The glucose from the saccharification reactor moves into the fermentation section to be converted into ethanol. The conversion from cellulose to glucose makes use of a novel enzyme developed by Iogen [4]. The enzyme is of a class of enzymes known as cellulases. These enzymes work to degrade the cellulose into glucose by “cutting” the glycosidic bond in the cellulose chains. This reaction is shown in Equation 1.



(1)

Based on data from Iogen’s patent [10], a 20-hour residence time was required to convert approximately 80% of the cellulose into glucose. The remainder of the cellulose is used to generate steam and electricity for the facility. The required reaction volume for the residence time was determined to be approximately 1.7 million gallons. Again, this volume was split into two equally sized tanks to help maintain a well-mixed system.

Cellulase activity is measured in an obscure unit known as filter paper units (FPU):

> “A unit of filter paper activity is defined as the number of micromoles of sugar produced per minute. The activity is calculated using the amount of enzyme required to produce 2 mg of sugar. A sample of Iogen’s cellulase was found to have 140 filter paper units per mL.” [4]

To achieve the 80% conversion in the 20-hour residence time, 0.45 mL/g feedstock and 0.32 mL/g feedstock must be used for corn stover and wheat straw respectively [4].

Cited References

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[2] Leksawasdi, Noppol et al. Mathematical modelling of ethanol production from glucose/xylose mixtures by recombinant *Zymomonas mobilis.* Biotechnology Letters. 2001. Vol. 23. Pg 1087-1093.

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Appendix A – Fermentation Model

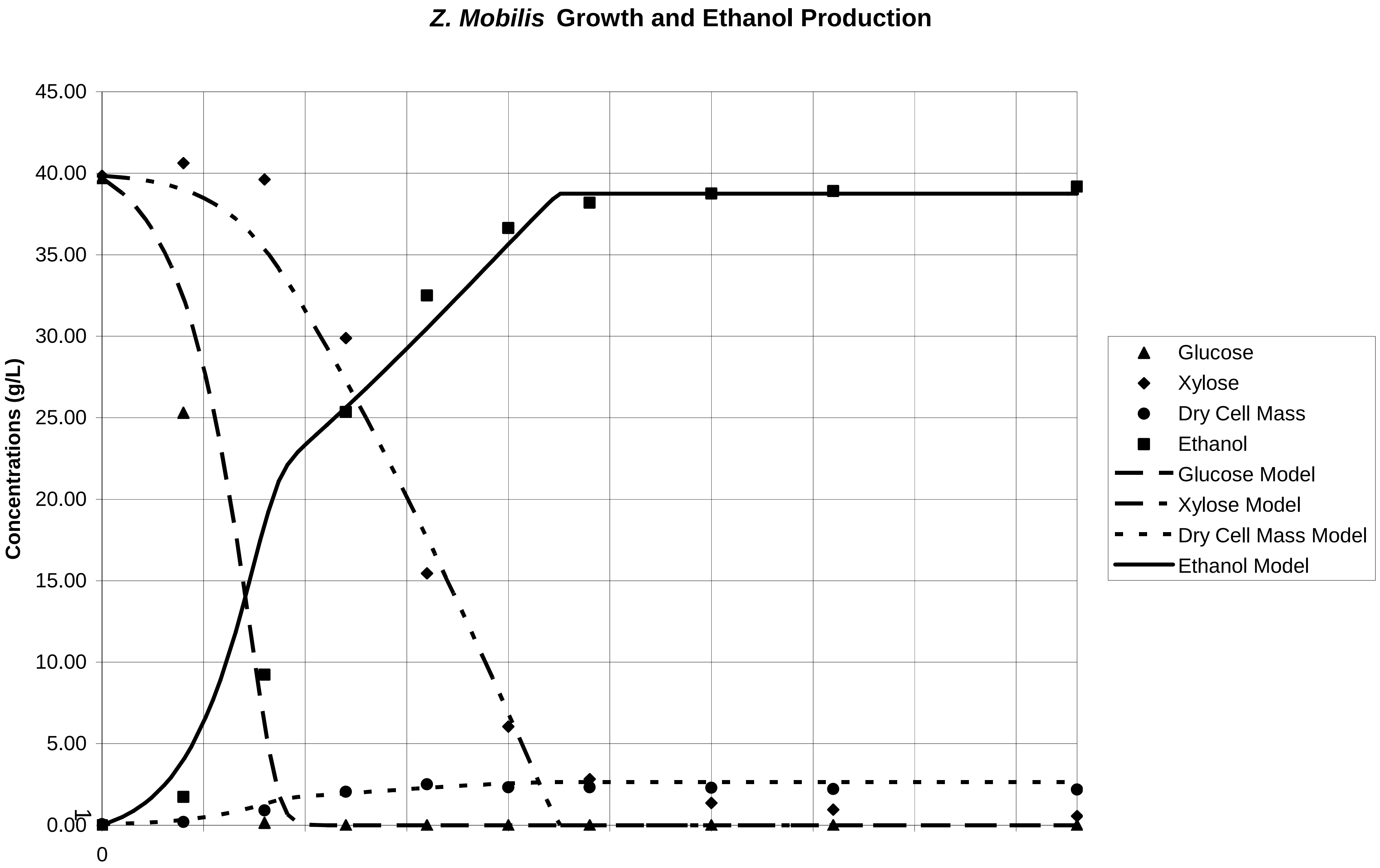

Figure A-1: Optimized Co-Fermentation Model for a Xylose-Glucose System

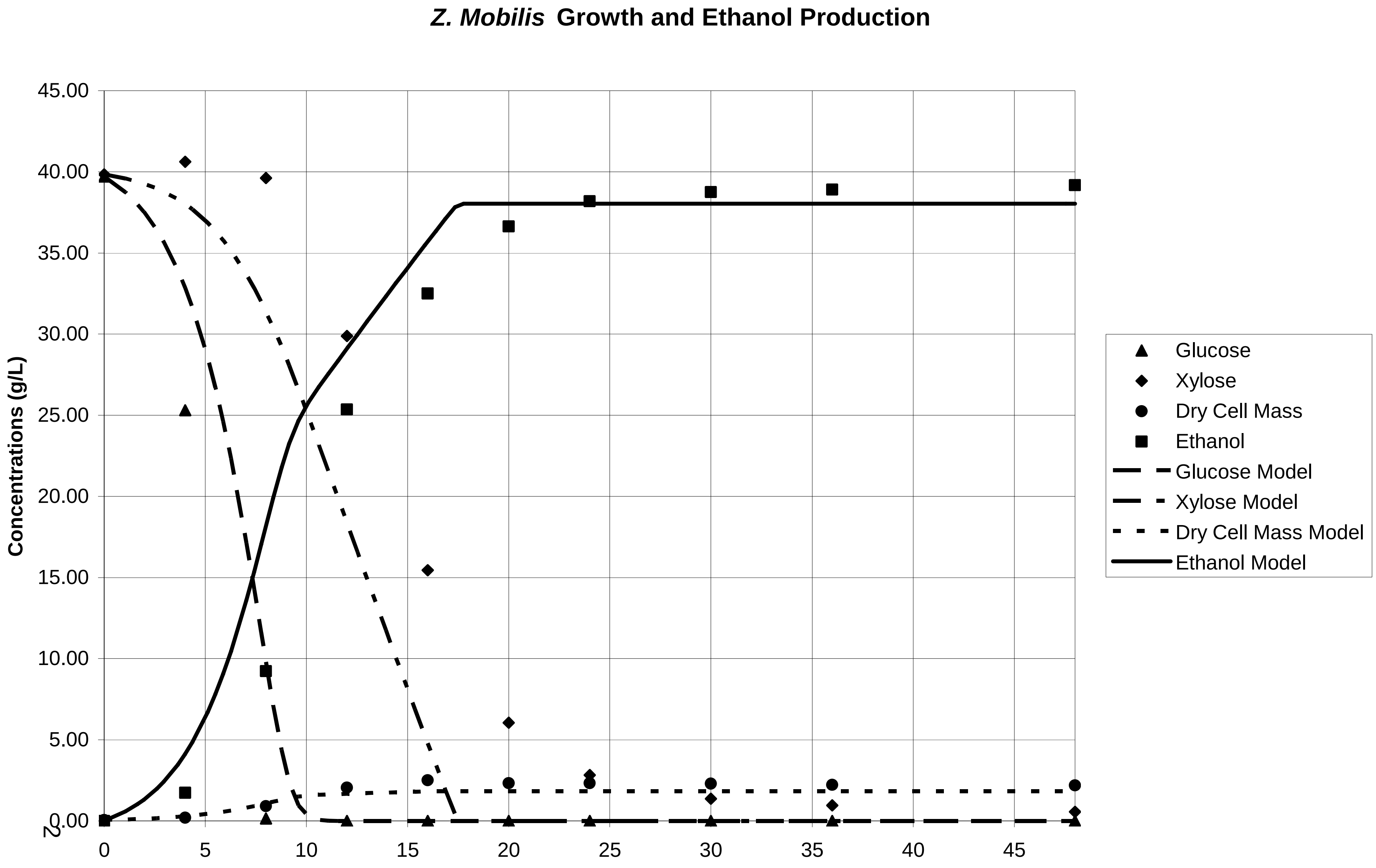

Figure A-2: Original Co-Fermentation Model for a Xylose-Glucose System