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# ECONOMIC EVALUATION OF THE MIT PROCESS FOR MANUFACTURE OF ETHANOL

By
D. M. Jenkins
T. S. Reddy



June 28, 1979

Work Performed Under Contract No. ET-78-X-01-3992

Battelle Columbus Laboratories
Columbus, Ohio

U.S. Department of Energy



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REPORT TO

U.S. DEPARTMENT OF ENERGY

on

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# EXECUTIVE SUMMARY

This report summarizes the results of an economic evaluation of the MIT process for the manufacture of ethanol from cellulosic residues. Conceptual process designs were developed for two cases, Case A which is based on the experimental data obtained to date, and Case B which hypothesizes the suppression of acid byproducts. Manufacturing costs, including profit, were estimated at $12.20/million Btu for Case A and $9.40/million Btu for Case B. These are equivalent to about $1.05 and $0.80/gal ethanol respectively. These economic estimates may be slightly on the low side since they do not consider feedstock storage nor working capital requirements. Nevertheless, the manufacturing costs for Case A appear to be comparable to those of the manufacture of ethanol from corn.

The plant size used for this analysis was 1500 ton/day corn stover. This is considered to be a realistic size. The conceptual plants make about 27 million gal/yr ethanol in Case A and 41 million gal/yr in Case B.

The MIT process appears to be one of the more promising programs being developed under contract for DOE. We would recommend that the process research be continued.

Three areas of concern were identified which must be investigated before the process can be commercialized. First, a satisfactory means of storage of corn stover and other agricultural residues must be developed. Second, a method to sterilize corn stover must be developed or it must be demonstrated that the MIT process can run continuously for extended periods with stover that has not been sterilized. Third, research must be done to demonstrate the recycle and reuse of process water.

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# INTRODUCTION

The objective of this study was to make an independent review of the economic feasibility of manufacturing ethanol by the MIT process. The MIT process consists of the simultaneous hydrolysis and fermentation of cellulosic agricultural residues utilizing a mixed culture of thermophilic bacteria. The bacteria are Clostridium thermocellum and C. thermosaccharolyticum. This mixed culture has the ability to hydrolyze and convert both cellulose and hemicellulose to a mixture of ethanol, acetic acid, and lactic acid.

Two cases were investigated in this study. The first case, Case A, is based on actual experimental results to date.* Case B is based upon an extrapolation of experimental results assuming that the formation of acetic and lactic acids can be suppressed. The fermentation conditions used as a basis for the economic evaluation are shown in Table 1. The yield of ethanol on corn stover is 18 percent for Case A and 27 percent for Case B.

The plant has been designed to manufacture fuel-grade (99.5%) ethanol. The plant was assumed to operate 24 hours per day, 330 days/year. The plant was sized to process 1500 ton/day corn stover and can produce about 27 million gallons per year in Case A and 40 million gallons in Case B.

Corn stover was selected as a typical agricultural residue because it is believed to be generally available and because the experimental data were based on corn stover. Assuming a typical corn belt yield of 100 bushels/acre and the removal of half the stover, about 400,000 acres of corn farms would be needed to supply the plant used in the study.

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* Cooney, C.L., Department of Nutrition and Food Science, Massachusetts Institute of Tecbnology, Personal Communications (April and June 1979).

TABLE 1. BASIS FOR PROCESS DESIGN

| | | | | Product Concentrations, g/l | | | | |
|---|---|---|---|---|---|---|---|---|
| Case | Productivity, g EtOH/l-hr | Dilution, $hr^{-1}$ | Initial Stover g/l | EtCH | Acetic Acid | Lactic Acid | Cells | Residue |
| A | 1.37 | 0.03 | 245 | 45 | 22 | 30 | 7.7 | 98 |
| B | 1.37 | 0.03 | 165 | 45 | 0 | 0 | 7.9 | 66 |

## PROCESS DESCRIPTION

The overall process block flow diagram used to estimate the cost of both cases is summarized in Figure 1. The plant consists of the following sections: feed preparation, fermentation, distillation, anaerobic digestion, steam plant, and waste treatment. There is no anaerobic digestion in Case B.

### Feed Preparation

The feed preparation section is very simple. It consists of two belt conveyors to feed the stover, a mill and a screen to reduce the size of corn stover, and a pneumatic conveyor system to convey the milled stover to the feed bins installed over the fermenters.

The storage section was not included in the economic analysis. Due to the low bulk density of corn stover (about 16 pounds dry stover per cubic foot), the volume required to support one day's operation is about 190,000 $ft^3$. Assuming the stover could be stored outside, 20 feet high, over 72 acres would be required for the storage area. Reclaiming the stover would be done with a combination of conveyor belts and bucket elevators. If the stover were stored in large bales, additional equipment would be needed to break these bales before milling.

The reader should note that the outdoor storage of corn stover for long periods of time has not been demonstrated. It is very likely that the cost for the storage section will be significant.

### Fermentation

The fermentation section consists of several continuous fermenters. Each fermenter is installed with a vibrating bin for continuously feeding the milled corn stover. The feeder bins are continuously loaded with the stover by a pneumatic conveyor; sterilized nutrients and recycled/makeup water is pumped into the fermenters through a separate line. The fermenters operate continuously at a dilution rate of 0.03 $(hour)^{-1}$ and 140 F (60 C).

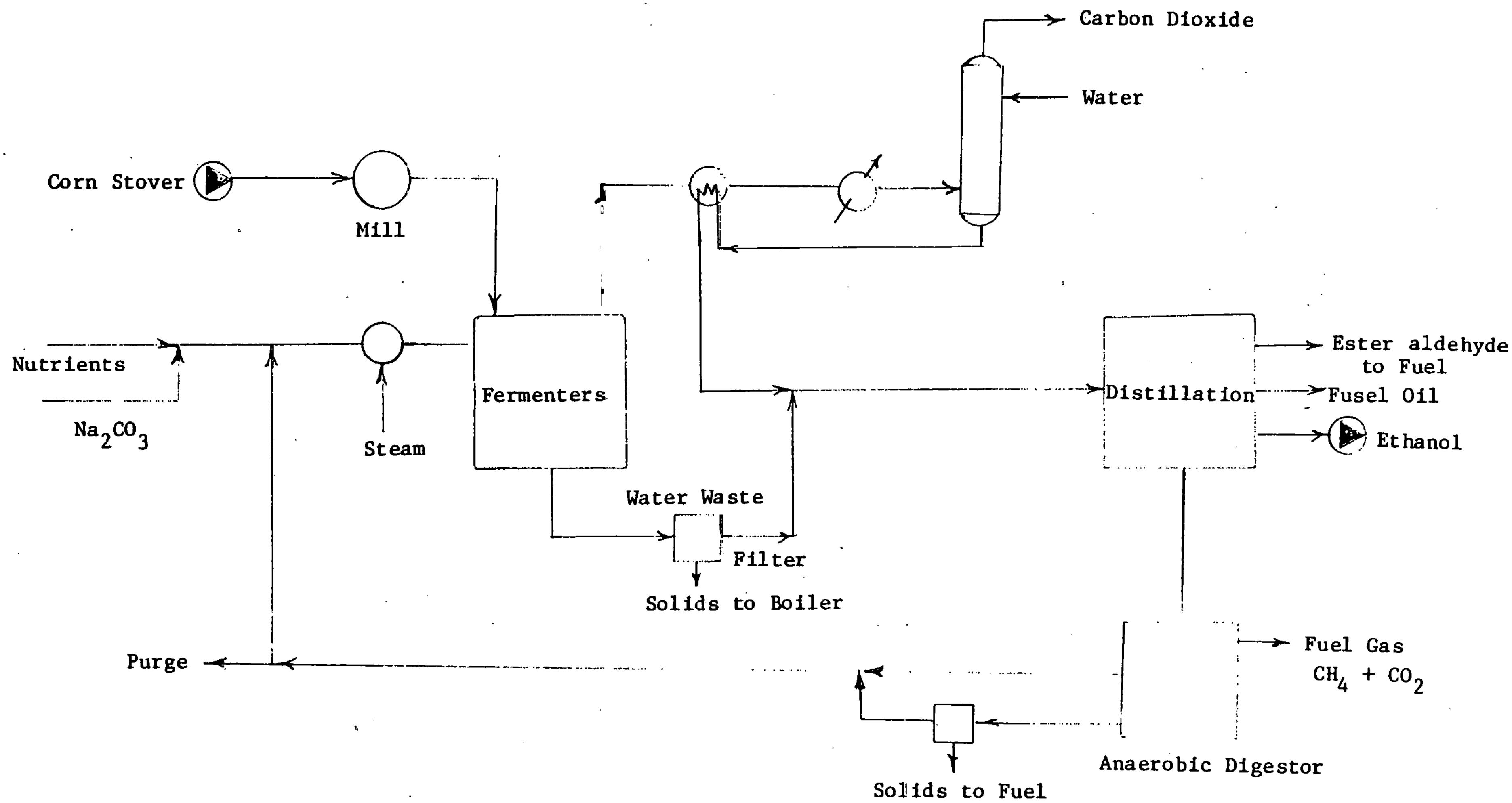


FIGURE 1. BLOCK FLOW DIAGRAM ALCOHOL FROM CORN STOVER

The beer from the fermenters is filtered and pumped into the beer tank. The solid residue obtained from the filters is used as fuel for steam generation. It was assumed that the filter cake would have 52 percent water and that a warm water wash of about 2 displacements would reduce the ethanol lost with the solids to a negligible amount. The carbon dioxide gas from the fermenters is cooled, and a water absorber is used to recover ethanol from the gas. The carbon dioxide is then vented to the atmosphere.

## Distillation

The distillation section of the corn stover ethanol process is based on a recent DOE report*. The distillation section consists of a stripper/rectifer, a dehydration tower, a hydrocarbon stripper, a fusel oil washer, and several heat exchangers. The Katzen design conserves energy.

The stillage from the distillation section goes to an anaerobic digester for Case A while it is recycled to the fermentation section directly without anaerobic digestion for Case B.

## Anaerobic Digestion

The anaerobic digester is designed for 3 days detention. Ninety percent of the supernatant liquid from the anaerobic digester is recycled to the fermentation section. The other ten percent is purged to the waste treatment system. The solids from the digester are recovered by means of a centrifuge and burned as plant fuel. A fuel gas (836 Btu/cu ft) containing methane and carbon dioxide is recovered and sold to nearby industrial customers. This relatively high heating value gas is obtained because much of the carbon dioxide from the digestion is retained in solution as sodium bicarbonate.

The costs of the anaerobic digestion section do not include any units for enriching fuel gas by removing carbon dioxide.

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* Moon, G.D. et al, "Grain Motor Fuel Alcohol Technical and Economic Assessment Study", Raphael Katzen Associates report to U.S. Department of Energy (December 1978).

Offsites

The steam plant is designed to consume all the combustible solid residues. It consists of two bagasse-fired boilers with a combined capacity of 190,000 pounds per hour 450 psig, 225 F superheat steam. Boiler efficienty of 63 percent was assumed. This steam plant supplies twice the process steam required for Case A.

The high-pressure steam is exhausted through back-pressure turbines which are connected to electric generators. The exhaust steam is used for the process requirements. Excess steam is sent through condensing turbines and is used to generate electricity.

The waste treatment cost is based on the bleed stream, boiler and cooling tower blowdowns. A BOD of about 2500 mg/1 has been assumed in the combined streams. The costs do not include equalization nor a primary clarifier but do include the aerated stabilization basin, suspended solids removal, effluent monitoring and sludge dewatering. A removal efficiency of about 97 to 98 percent has been assumed. This removal corresponds to "best practicable control technology".

## PROCESS ECONOMICS

The process economics for the manufacture of ethanol by the MIT process are summarized in Tables 2 and 3. For Case A, which represents the best experimental results to date, the manufacturing cost including profit is estimated at about \$12.20/MM Btu (or about \$1.03/gal). If the process improvements hypothesized in Case B can be achieved, the estimated manufacturing costs would be reduced to about \$9.40/MM Btu (or \$0.80/gal). These economic estimates may be slightly on the low side since they do not consider feedstock storage nor working capital requirements. Nevertheless, it appears that the cost of manufacturing ethanol using the best experimental results to date is in the same range as the manufacture of ethanol from corn.

The estimated capital requirement for a plant processing 1500 ton/day corn stover is estimated at \$34.3 million for Case A and \$31.4 million for Case B. The daily capacities are 83,400 gal and 123,800 gal ethanol, respectively. All costs are expressed in 1979 dollars. The offsites represent about half of the total plant capital investment. Steam and electricity generation account for about 70 percent of the fixed investment in offsites. Working capital is not included in the estimate; it would probably be significant.

There is a considerable amount of solid residue recovered from the process. Most of this residue is unconverted corn stover, but it also includes cells generated in the fermentation and the anaerobic digestion. In the conceptual process design, all of this solid residue is burned and the heat used to generate steam. In Case A, half of the steam generated is not needed for the process. This excess steam was used to generate electricity.

A credit for this surplus in electricity was taken at 1.6¢/kwhr. This is the approximate break-even price for this electricity. Therefore, the overall process has not been penalized for the additional capital required to generate excess electricity and steam. Fortunately, the break-even cost of generating the surplus power is about equal to the price that might be expected from a large electric utility system. Electric

TABLE 2. MANUFACTURING ECONOMICS, MIT ETHANOL PROCESS CASE A, 1979 $
PLANT CAPACITY 1500 TON STOVER/DAY, 83,400 GAL ETHANOL/DAY

| | Feed Preparation | Fermentation | Distillation | Anaerobic Digestion | Offsites | Total |
|---|---|---|---|---|---|---|
| Fixed Investment, Million $ | 0.91 | 8.22 | 4.01 | 6.18 | 14.99 | 34.31 |
| Fixed Capital Related | 0.09 | 0.82 | 0.40 | 0.61 | 1.49 | 3.41 |
| Stover, \$30/dry ton | - | 6.42 | - | - | - | 6.42 |
| Soda Ash, \$80/ton | - | 0.52 | - | - | - | 0.52 |
| Corn Steep Liquor, \$101/ton | - | 1.77 | - | - | - | 1.77 |
| Other Materials | - | 0.71 | - | - | - | 0.71 |
| Steam, \$0.96/1000# (a) | - | 0.05 | 0.27 | - | (0.32) | - |
| Power, 3.2¢/kwhr | 0.02 | 0.03 | 0.02 | 0.01 | (0.08) | - |
| Power (surplus), 1.6¢/kwhr | | | | | (0.65) | (0.65) |
| Direct Labor Related | 0.11 | 0.21 | 0.11 | 0.05 | 0.21 | 0.69 |
| Maintenance | 0.02 | 0.21 | 0.10 | 0.05 | .13 | 0.51 |
| Fuel Gas Credit, \$2.00/MM Btu | - | - | - | (1.17) | - | (1.17) |
| TOTAL | 0.24 | 10.74 | 0.90 | (0.45) | 0.78 | 12.21 |

(a) Low steam cost results from use of low cost bagasse boilers and no fuel charges for combustible residue.

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TABLE 3. MANUFACTURING ECONOMICS, MIT ETHANOL PROCESS CASE B, 1979 $
PLANT CAPACITY 1500 TON STOVER/DAY, 123,800 GAL ETHANOL/DAY

| | Feed Preparation | Fermentation | Distillation | Offsites | Total |
|---|---|---|---|---|---|
| Fixed Investment, Million $ | 0.91 | 9.63 | 5.21 | 15.45 | 31.20 |
| Fixed Capital Related | 0.06 | 0.65 | 0.35 | 1.03 | 2.09 |
| Stover, $30/dry ton | | 4.32 | | | 4.32 |
| Soda Ash, $80/ton | - | - | | | |
| Corn Steep Liquor, $101/ton | | 1.77 | | | 1.77 |
| Other Materials | | 0.71 | | | 0.71 |
| Steam, $0.96/1000# | | 0.05 | 0.27 | (0.32) | - |
| Power, 3.2¢/kwhr | 0.01 | 0.03 | 0.02 | (0.06) | - |
| Power (surplus), 1.6¢/kwhr | - | - | - | (0.36) | - |
| Direct Labor Related | 0.07 | 0.18 | 0.07 | 0.14 | 0.46 |
| Maintenance | 0.02 | 0.17 | 0.09 | 0.09 | 0.37 |
| TOTAL | 0.16 | 7.88 | 0.80 | 0.52 | 9.36 |

DMJ/ 6/79

power used in the process was charged at 3.2¢/kwhr, which is the price that a plant would probably pay to purchase power from an electric utility. Since this power was generated within the system, an equivalent credit was taken in the offsite section.

In Case A, acids made in the process are converted to fuel gas by anerobic digestion. A $2/MM Btu credit was taken for the fuel gas, which equates to about $1.17/MM Btu of ethanol product. This credit is equivalent to the maximum lawful wellhead price for interstate gas from new onshore production wells. This gas price also approximates the price obtained in new intrastate gas contracts. While the byproduct fuel gas produced in Case A is not quite pipeline quality, the gas could be easily upgraded by absorbing the acid gases. The alcohol plant would be located in the corn belt, closer to major gas markets than most gas production. A change of 20¢/MM Btu in the value of byproduct fuel gas would result in about a 12¢/MM Btu change in the alcohol product price.

Materials constitute the major operating cost (77 percent for Case A). Corn stover represents about half the total manufacturing cost. There are also significant costs for the nutrients required for the fermentation. For the purpose of analysis, it was assumed that all nutrients added to the process would be removed with the residues rather than recycled.

In estimating the process economics, capital charges were assessed assuming a 12 percent discounted cash flow return on fixed investment, a 3-year construction period, a 20-year economic life, an 11-year tax life, and a 50 percent effective tax rate. It was further assumed that the plant would operate at 70 percent capacity during the first year and at full capacity thereafter. No provision was made for return on working capital nor for startup costs. Land costs are not included. Other assumptions used in estimating the process costs are summarized in Table 4.

TABLE 4. BASIS FOR THE COST ESTIMATION

| | |
|---|---|
| Plant capacity | 1500 tons per day dry corn stover |
| Operation | 24 hours per day, 330 days per year |
| Corn stover | \$30/dry ton |
| Electricity | \$0.032/kwhr |
| Byproduct electricity | \$0.016/kwhr |
| Fuel gas byproduct | \$2.00/MM Btu |
| Urea | \$175/ton (45% N) |
| $CaCl_2$ | \$93/ton (77.8% flakes) |
| $MgSO_4 \cdot 7H_2O$ | \$12.60/100 lb |
| Corn steep liquor | \$101/ton |
| $H_3PO_4$ | \$22.60/100 lb |
| $FeSO_4 \cdot 7H_2O$ | \$53/ton |
| Maintenance | 6% fixed investment for process units, 2% for offsites |

## DISCUSSION

The conceptual process appears to be one of the most promising methods for conversion of cellulosic biomass to liquid fuels. Even without the improvement of the process to eliminate coproduction of acetic and lactic acids in the fermentation, the manufacturing cost of fuel grade ethanol appears competitive with that for ethanol from grain. The MIT process appears to be more economic and significantly less capital intensive than the previously costed Purdue process.*

A further advantage of the MIT process over other conceptual processes is that all byproducts are energy (fuel gas and electricity). Many processes have an animal feed component as a byproduct which could present a marketing barrier to some manufacturers.

In spite of the apparent advantages of the MIT process, we have three concerns which could affect the overall economics. The first concern relates to the storage of the corn stover or other agricultural residue. To our knowledge, no comprehensive studies have been made of the best methods to store corn stover. Because the corn is harvested during a brief period, an entire year's supply must be stored to enable year-round operation. The very real problems of degradation during storage, protection from the weather, handling equipment, and the possibility of spontaneous combustion have generally been assumed away in most analyses (including this one). Therefore, we recommend that DOE investigate the storage problem which applies to all processes for the utilization of cellulosic residues.

A second concern specific to the MIT process relates to a need for aseptic operation. Although provision is made to sterilize the liquids and dissolved solids entering the fermenters, no provision was made in the conceptual design for sterilization of the stover. It is hoped that the combination of elevated fermentation temperature and moderate alcohol concentration in the fermenters will prevent infection by wild micro-organisms. Nevertheless, it remains to be demonstrated that a sustained

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* Jenkins, D.M., Reddy, T.S., and Harrington, J., "Economics of Manufacturing Liquid Fuels From Corn Stover", Battelle report to Department of Energy (January 1979)

continuous fermentation can be operated without sterilization of the stover. Investigation of sterility requirements should be high on the list of research priorities. If sterilization is required, there would be plenty of steam available and the impact on overall costs should not be great.

Our third concern relates to the recycle of liquids from the anaerobic digestion or still. While demonstration of continuous operation with recycle should be part of a future process development program, current efforts should attempt to identify the composition of the recycle stream. Furthermore, preliminary experiments can be conducted to determine whether toxic materials will build up in the recycle of a continuous process.

# APPENDIX A

## PROCESS DETAILS

Process Flow Sketches

Equipment List

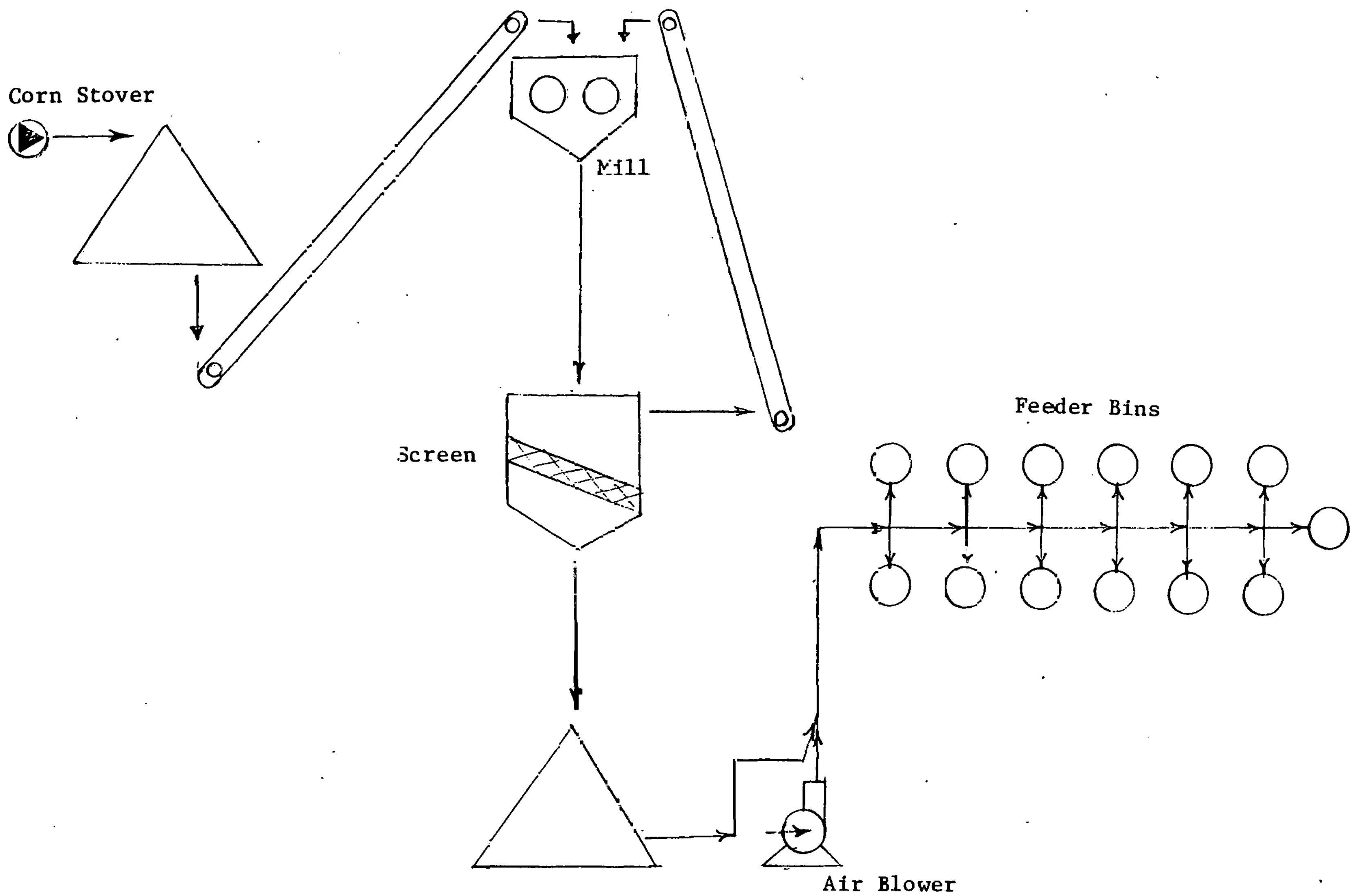


FIGURE A-1. FEED PREPARATION

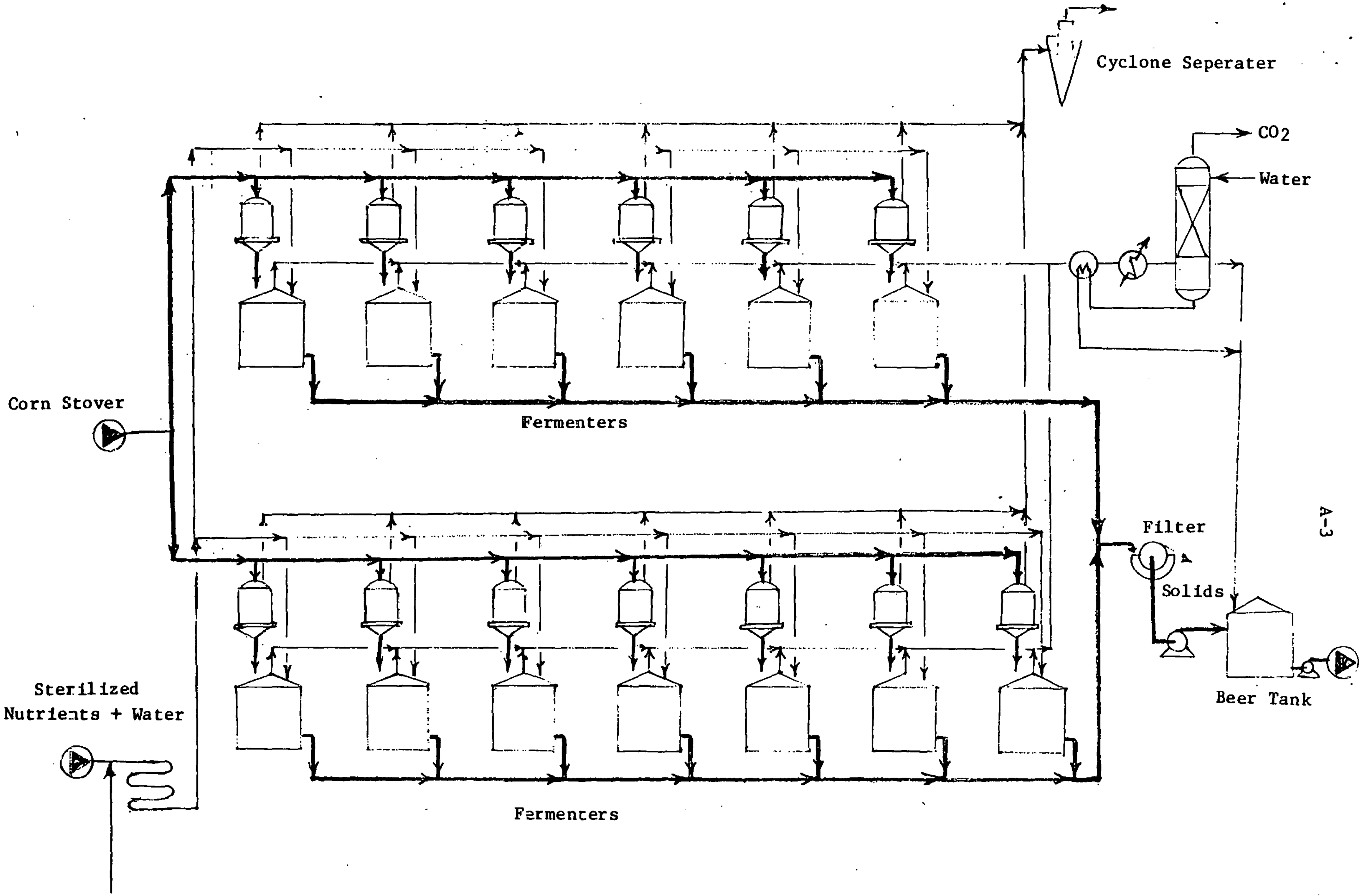


FIGURE A-2. FERMENTATION SECTION

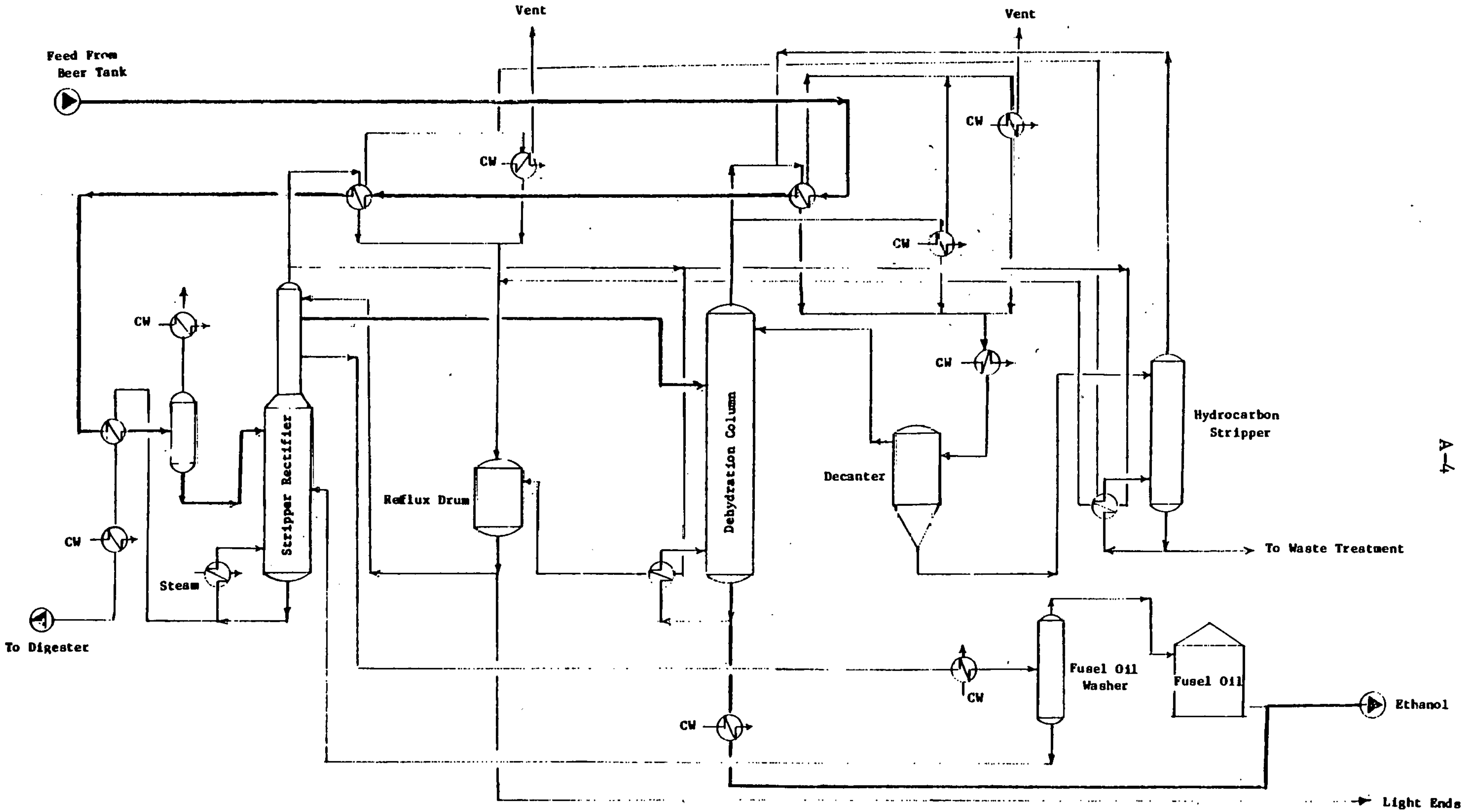


FIGURE A-3. DISTILLATION SECTION

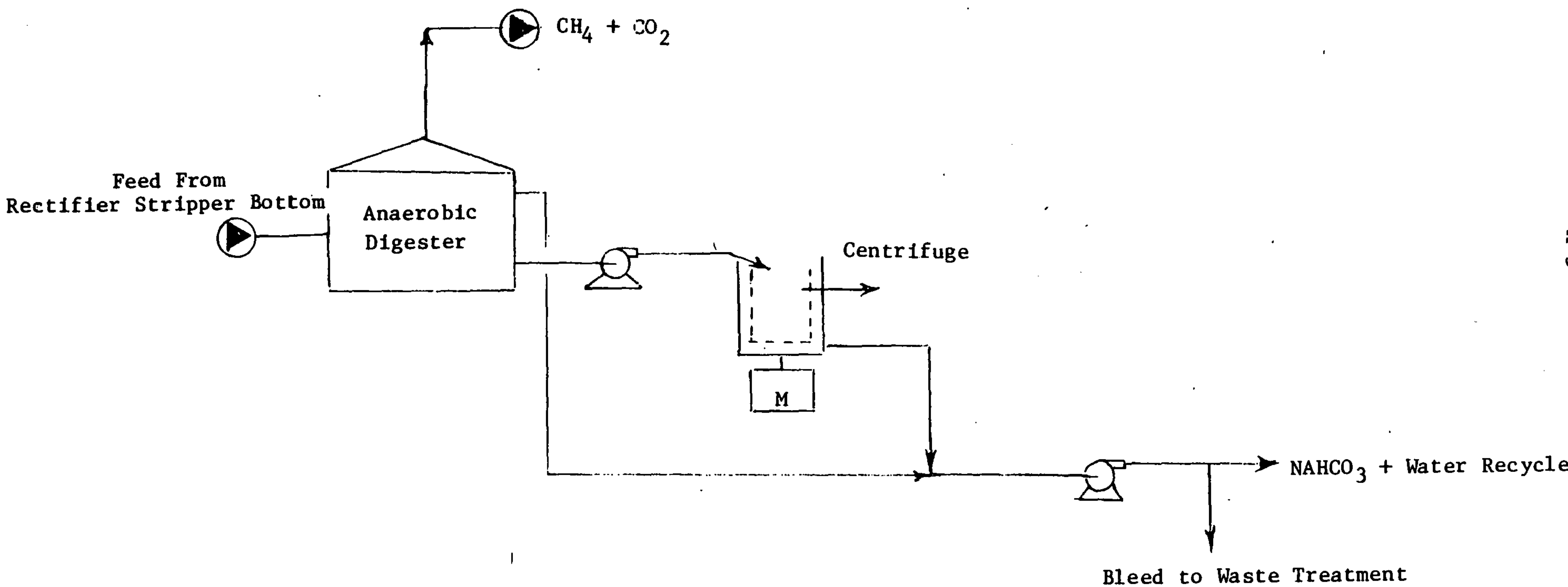


FIGURE A-4. DIGESTER SECTION

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| **Feed Preparation** | | | | |
| Belt conveyers | 58.6 tph | 2 | 21,000 | |
| Hammer mills | 58.6 tph | 1 | 61,000 | |
| Vibrating screens | 58.6 tph | 1 | 61,000 | |
| Pneumatic conveyer systems | | 13 | 9,820 | |
| Hopper bin feeders | 2,000 gal | 13 | 9,960 | |
| Subtotal feed preparation | | | | 768,700 |
| Contingency + fee @ 18% | | | | 138,366 |
| Total feed preparation | | | | 907,066 |
| **Fermentation** | | | | |
| Phosphoric acid tank | 2,000 gal, ss | 1 | 93,000 | |
| Corn steep liquor tank | 200,000 gal, cs | 1 | 65,500 | |
| $Na_2CO_3$ storage | 8618 $ft^3$ | warehouse | - | |
| Mix tanks $Na_2CO_3$ | 40,000 gal, cs | 2 | 24,000 | |
| Nutrient mix tanks | 2,000 gal, cs | 2 | 9,850 | |

MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| Fermentation (con't) | | | | |
| Corn steep liquor | 20 gpm | 1 | 5,400 | |
| $Na_2CO_3$ sol. | 72 gpm | 1 + 1 | 9,000 | |
| Nutrients sol. | 24 gpm | 1 + 1 | 5,400 | |
| Phosphoric acid | 8 gpm | 1 + 1 | 3,800 | |
| Sterilizer | 63.9 MM Btu/yr | 2 | 108,200 | |
| Fermenters, coned roof sloped bottom, 35' dia x 35' high | 250,000 gal, cs | 13 | 73,300 | |
| Off-gases exchanger | 2300 $ft^2$ | 1 | 93,558 | |
| Off-gases cooler | 50,026 $ft^2$ | 2 | 172,587 | |
| Scrubber bottoms pump | 100 gpm, 5 hp | 1 | 842 | |
| Cooler water pump | 1046, 50 hp | 1 | 4,000 | |
| Scrubbing water pump | 90, 4 hp | 1 | 842 | |

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| Fermentation (con't) | | | | |
| Fermenter discharge pump | 95 gpm | 13 + 2 | 842 | |
| $CO_2$ off-gas scrubber | 5' dia x 10' high | 1 | 10,400 | |
| Rotary filter | 760 $ft^2$ & 20 $lbs/hr/ft^3$ | 4 | 181,500 | |
| Filtrate pump | 304 gpm, 50 hp | 4 | 21,000 | |
| Cake conveyor | 56 tpd | 1 | 3,300 | |
| Beer tank | 200,000 gal, coned roof, sloped bottom | 1 | 66,300 | |
| Distillation feed pump | 1520 gpm | 2 | 5,000 | |
| Subtotal fermentation equipment | | | | 6,965,852 |
| Contingency + fee @ 18% | | | | 1,253,853 |
| Total Fermentation | | | | 8,219,705 |

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| **Distillation** | | | | |
| Stillage pump | 1283 gpm | 2 | 4,400 | |
| Stripper/rectifier reboiler | Q = 47.2 MM $\frac{\text{Btu}}{\text{hr}}$<br>A + 3350 ft each<br>304 ss/cs | 2 | 72,800 | |
| Degasser drum | 5' dia x 6' high, cs | 1 | 5,500 | |
| Dehydration column reboiler & pump | 2000 gpm, 30' tdh | 1 | 2,500 | |
| Stripper/rectifier | 75 psig | 1 | 167,600 | |
| Degassing vent condenser | Q = 500,000 Btu/hr<br>A = 100 $ft^2$ 304 ss | 1 | 5,200 | |
| Vapor condenser/ preheater | Q = 4.82 MM Btu/hr<br>A = 365 $ft^2$, 304 ss/cc | 1 | 22,600 | |
| Rectifier vent condenser | Q = 4.13 MM Btu/hr<br>A = 1020 $ft^2$ | 1 | 27,600 | |
| Rectifier reflux pump | 360 gpm, 170' tdh | 1 | 2,600 | |

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| **Distillation (con't)** | | | | |
| Rectifier reflux drum | 6' dia. x 5' high | 1 | 3,100 | |
| Product cooler | Q = 1.7 MM Btu/hr<br>A = 193 $ft^2$, 304 ss/cs | 1 | 14,000 | |
| Condenser/reboiler | Q = 18 MM Btu/hr<br>A = 3240 $ft^2$, 304 ss/cs | 1 | 127,000 | |
| Dehydration reboiler pump | 1375 gpm, 30' tdh, 15 hp | 1 | 3,500 | |
| Dehydration tower | 102' dia, 50 trays,<br>15 psig, 250 F, cs shell,<br>304 ss trays | 1 | 113,000 | |
| Product pump | 83 gpm, 72' tdh | 1 | 830 | |
| Dehydration condenser perheater | Q = 12.93 MM Btu/hr<br>A - 2450 $ft^2$, 304 ss/cs | 1 | 66,000 | |
| Dehydration condenser | Q = 22.40 MM Btu/hr<br>A = 82 $ft^2$, 304 ss/cs | 1 | 3,960 | |

MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| Distillation (con't) | | | | |
| Dehydration vent condenser | Q = 550,000 Btu/hr<br>A = 82 $ft^2$, 304 ss/cs | 1 | 5,000 | |
| Decanter | 10,000 gal, cs<br>15 psig | 1 | 15,300 | |
| Dehydration reflux cooler | Q = 4.62 MM $\frac{Btu}{hr}$<br>A = 722 $ft^2$, 304 ss/cs | 1 | 27,000 | |
| Stripper feed pump | 18 gpm, 93' tdh | 1 | 700 | |
| Dehydration reflux pump | 330 gpm, 120 tdh | 1 | 1,100 | |
| Hydrocarbon stripper | 31" dial, 30 trays,<br>cs shell, cs trays | 1 | 16,500 | |
| Condenser/reboiler condensate pump | 275 gpm, 40' tdh, 304 ss | 1 | 1,100 | |
| Stripper reboiler pump | 66 gpm, 50' tdh, 1.5 hp<br>304 hp | 1 | 8,300 | |

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| Distillation (con't) | | | | |
| Stripper reboiler condensate pump | 31 gpm, 40' tdh | 1 | 680 | |
| Hydrocarbon stripper reboiler | Q = 3.3 MM Btu/hr<br>A = $1650\ ft^2$ 304 ss/cs | 1 | 47,000 | |
| Fusel Oil cooler | A = $27\ ft^2$, 304 ss/cs | 1 | 2,100 | |
| Fusel Oil washer | 250 gal, cs | 1 | 1,600 | |
| Wash water pump | 0.5 hp | 1 | 700 | |
| Fusel oil storage tank | 3000 gal, cs | 1 | 3,600 | |
| Fusel oil pump metering | 5.5 gpm, 150' tdh | 1 | 400 | |
| Stripper/rectifier feed heat exchanger | A = $4882\ ft^2$, cs/ss<br>Q = 73.23 MM Btu/hr | 1 | 154,095 | |
| Cooler | Q = 23.3 MM Btu/hr<br>A = $956\ ft^2$, cs/ss | 1 | 38,982 | |
| Subtotal Distillation Equipment | | | | 3,399,966 |
| Contingency + fee @ 18% | | | | 611,994 |
| Total Distillation | | | | 4,011,960 |

## MAJOR EQUIPMENT LIST

| Item | Basis | No. of Units | Unit Cost | Installed Cost |
|---|---|---|---|---|
| **Anaerobic Digestion** | | | | |
| Anaerobic digester | 100' dia x 40' deep | 3 | 5,200,000 | |
| Supernatant recycle pump | 1263 gpm 100' tdh | 1 | 4,400 | |
| Sludge settling unit | 15 gpm | 1 | w/anaerobic digester | |
| Sludge settler supernatant pump | 15 gpm | 1 | w/anaerobic digester | |
| Centrifuge | 15 gpm | 1 | 11,000 | |
| Filtrate pump | 15 gpm | 1 | - | |
| Solids conveyor | 1.4 tdh | 1 | 2,200 | |
| Subtotal Anaerobic Digestion | | | | 5,236,398 |
| Contignecy + fee @ 18% | | | | 942,552 |
| Total Anaerobic Digestion | | | | 6,178,950 |

| | Basis | Unit | Total Installed Cost |
|---|---|---|---|
| Offsites | | | |
| Steam generation with auxiliaries | 95,000 lb/hr, 450 psig 225 F S.H. | 2 | 5,300,000 |
| Electrical generation and distribution | 13,400 kw | – | 3,448,000 |
| Cooling tower | 15,937 gpm, 20 F rise | – | 1,237,000 |
| Wastewater | | | 950,000 |
| Product storage | 2,000,000 | | 516,000 |
| Offsite piping | | | 330,000 |
| Misc. buildings | | | 395,000 |
| Site preparation | | | 525,000 |
| | | | 12,701,000 |
| Cost + fee @ 18% | | | 2,286,000 |
| Total | | | 14,987,000 |



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