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DESIGN, ENERGY, AND ECONOMIC ANALYSIS OF SMALL SCALE ETHANOL FERMENTATION FACILITIES

presented by

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has been accepted towards fulfillment of the requirements for

M.S. degree in Chemical Engineering

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Date June 11, 1981

DESIGN, ENERGY, AND ECONOMIC ANALYSIS OF SMALL SCALE ETHANOL FERMENTATION FACILITIES

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1981

ABSTRACT

DESIGN, ENERGY, AND ECONOMIC ANALYSIS OF SMALL SCALE ETHANOL FERMENTATION FACILITIES

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Industrial scale fermentation ethanol production from corn has been proposed as a way to produce liquid fuel, but can only achieve a positive liquid energy balance and positive economics by careful plant design. In comparison, small scale production of alcohol on corn-producing farms and farms which use the by-product might reduce costly corn drying and transportation energy charges involved in industrial scale production. If corn stillage could be stored in a wet state, it would be fed to livestock without being dried and the ethanol product would be used by farm equipment as fuel.

The purpose of this study was to determine the requirements for a small scale ethanol production scheme with relatively low energy requirements and evaluate the overall energetic and economic feasibility of the processes compared to large scale industrial production. This project also involved the construction of a pilot small scale ethanol production facility by the combined

efforts of the Chemical Engineering, Agricultural Engineering, and Animal Science Departments of Michigan State University with a grant from the Michigan Department of Agriculture. The Chemical Engineering Department was responsible for the design, construction, and operation of the distillation apparatus and the energy and material balances around the system. This pilot facility was used in this study as a source of data to support the designs of farm scale processes.

Three small scale ethanol production schemes or scenarios were evaluated in this study. Scenario I, Farm Production of Anhydrous Ethanol, was used as a base case of 15 farms, each producing 100,000 gallons of anhydrous ethanol per year, in which all processing to produce anhydrous ethanol was done entirely on each farm. Scenarios II and III use large scale process centralization variations on the base case in an attempt to reduce the overall energy requirements of the process. Scenario II, Centralized Azeotropic Distillation, is the same as Scenario I except for a centralized large scale azeotropic distillation facility for water extraction from the ethanol-water azeotrope to produce the anhydrous ethanol product. Scenario III, Centralized Ethanol Rectification and Azeotropic Distillation, incorporates centralized large scale ethanol rectification for low grade ethanol refining together with azeotropic distillation for anhydrous ethanol production.

The best overall production scheme was Scenario III which had an overall energy efficiency of 0.694 BTU out/BTU in, compared to 1.00 for industrial scale production (5 million gallons of anhydrous ethanol per year). This lower energy efficiency for small scale production is significant since the corn stillage by-product was not dried in the small scale case and was dried in the industrial scale case. The energy losses in the small scale process can be attributed to the inefficiencies of the small scale steam boiler and low pressure steam and heat losses due to large surface to volume ratios of small scale equipment. The energy savings from feeding wet corn stillage and lower transportation requirements did not offset these small scale energy inefficiencies and resulted in a significant decrease in the overall energy efficiency compared to industrial scale production. Scenario III produced anhydrous ethanol for $3.77 per gallon, which could be produced for $1.98 per gallon by an industrial scale facility. This increased cost of ethanol is primarily due to greater fuel, labor, and equipment costs of small scale production. Small scale fermentation ethanol production from corn is not economically or energetically favorable, compared to industrial scale production, as shown by these results.

TABLE OF CONTENTS

LIST OF TABLES

Table		Page

LIST OF FIGURES

I. INTRODUCTION

Ethanol production from biomass has been considered as an alternative liquid fuel since gasoline was first used as a fuel, and is revived whenever oil prices increase or availability is questionable. Foreign control of oil reserves and dramatic price increases have again forced many countries to consider using ethanol as a fuel. The United States, with its abundant grain reserves, is a prime candidate for fermentation ethanol production. Many Midwestern states, together with the United States government, are promoting and giving economic incentives for ethanol production and use.

Large scale production of ethanol by fermentation of biomass is currently in practice in many parts of the United States. The energetic and economic feasibility of large scale production is therefore well known and is usually favorable.[6,7,12] One of the problems encountered with large scale fermentation ethanol production from corn, which is popular in the Midwest, is the large energy requirements of the overall process. Energy is not only required for corn grinding, cooking, fermentation, and distillation, but is also needed for the drying of the corn stillage byproduct and the transportation of all feedstocks and products. Small scale fermentation ethanol production (less than one million gallons of anhydrous ethanol per year) on a corn-producing farm is one proposed method for reducing some of these energy requirements. On-farm production might reduce some of these energy requirements by the close proximity of the corn to the plant, a local market for ethanol as a fuel for farm equipment, and the use of the corn stillage by-product as a livestock feed on the farm. A substantial energy savings might also be realized by feeding the grain by-product wet instead of drying it. The storage life of wet grain by-product is still being researched. Large scale plants dry the by-product because of the storage, transportation, and marketing problems involved with a wet-corn stillage by-product. The small scale facility could feed the wet by-product on the farm immediately after processing and alleviate these storage, transportation, and marketing problems. If it is determined that wet by-products can be stored and fed to livestock, the feeding of wet grain by-product on the farm could also save energy and costs normally incurred in drying the by-product. This method of processing ethanol has obvious energy-saving advantages, but it also has disadvantages with energy losses through small scale process inefficiencies. The energetic and economic feasibility of such a system has not been researched in the literature.

The purpose of this study is to evaluate three small scale ethanol production schemes, or scenarios (chosen for their low energy and economic requirements) to find the optimal production schemes, and determine the overall energetic and economic feasibility of such a process.

All material and energy balance data used in this study were obtained from a pilot facility constructed on the Michigan State University campus by joint effort of the Chemical Engineering, Agricultural Engineering, and Animal Science Departments with a grant from the Michigan Department of Agriculture. The pilot small scale facility was used to evaluate all facets of on-farm small scale ethanol production.

The distillation column design, construction, and optimization and the overall material and energy balances were carried out by the Chemical Engineering Department.

Livestock nutrition from by-product feeding and the utilization of the ethanol product by farm equipment were studied by the Animal Science and Agricultural Engineering Departments.

II. PRODUCTION SCHEMES

The objective of evaluating different small scale ethanol production schemes or scenarios was to choose an overall process of relatively low energy and economic requirements. Typical farming conditions in Michigan were used to provide a realistic basis for the comparison.

An overall knowledge of the problems and limitations of small scale fermentation ethanol production is required in devising a base case for the scenarios and is not available in the current literature. The experiences gained from constructing and operating the small-scale fermentation ethanol facility at Michigan State were used as a source of reliable data for this study. The experimental design, operation procedure and problems, and overall results of the pilot facility are documented in Appendix A. These results were then used to support the design of an efficient, but realistic, base case on farm small scale ethanol production facility (Scenario I) and two variations in the base design (Scenarios II and III).

The basis for the scenarios is outlined in Table 1. A biomass feedstock of corn was used because of the availability of corn in the Midwestern states, its high ethanol yield in comparison to other feedstocks[11] and

TABLE 1. Basis for Scenarios

Biomass Feedstock: Corn

Location: Saginaw Valley Area, Michigan

Ethanol Production: 100,000 gallons Anhydrous Ethanol per Farm per Year[a]

Facility Utilization: 8000 Hours (48 Weeks) per Year

Ethanol Yield: 2.34 Gallons Anhydrous Ethanol per Bushel[b] (56 lbs @ 15.5% moisture)

Farm Size: 535 acres of Corn per Farm[c]

Corn Usage: 42,735 Bushels per Year

Number of Farms: 15 Farms (in 30-Mile Radius)[d]

Byproduct Use: "Wet" corn stillage byproduct with filler fed to livestock on farm[e] (1917 lbs dry/day)

Required Livestock: 780-960 Beef Cattle per Farm, or 2550-2760 Hogs per Farm[f]

Process Energy Efficiencies: 62% Boiler Efficiency
35% Electric Efficiency

Fuel Source: Coal ($40/Ton)

Electricity: Purchase (Coal or Nuclear: $0.032/kwh)

[a]Largest production size for one operator per shift

[b]Average yield of experimental facility (Appendix A)

[c]Size required for given yield and 80 bushels per acre (average for Saginaw Valley Area)[10]

[d]Average distribution of farms with 535 acres or more of corn in Saginaw Valley Area[10]

[e]"Wet" means that no moisture is removed from stillage.

[f]Using 7-15% corn byproduct ration.[11]

the substantial amount of information available on large scale ethanol production for comparison. The Saginaw Valley area in Michigan was chosen for the study because it is in the heart of Michigan's corn belt. The ethanol production of 100,000 gallons of anhydrous ethanol per farm per year was used because it is the maximum possible size for one operator per shift and is a minimum in labor cost per gallon produced. This estimate is based on the experience gained at the M.S.U. facility. This production size requires a minimum of 535 acres of corn per farm using an average ethanol yield of 2.34 gallons of anhydrous ethanol per bushel of corn and a corn yield of 80 bushels per acre, which is consistent with yields in the Saginaw Valley area. The ethanol yield of 2.34 gallons of anhydrous ethanol per bushel is an average experimental yield from the batch fermentation studies documented in Appendix A. The fifteen farms in the study were assumed to be within a 30-mile radius, which is the average distribution of farms growing 535 or more acres of corn in the Saginaw Valley area.(10) The corn stillage by-product of each farm would be fed wet to livestock without any moisture being removed to save energy used in drying. Dry fillers would also be used to lower the overall moisture content and to add required nutrients to the feed. The livestock requirements for each farm are 780-960 beef cattle or 2,550-2,760 hogs using a 7-15% ration of by-product.(11)

A boiler efficiency of 62% was used to account for losses of energy in the production of steam from a coal fired boiler. Coal was used for the process since the purpose of the project is to produce liquid fuel, which is in short supply, from non-liquid fuel materials which are not in short supply, such as coal. An electrical efficiency of 35% was used to represent the energy losses in production and usage of electricity. Coal or nuclear power was assumed to be the source of the electricity used in the process.

Large scale fermentation ethanol production from corn is a well documented process in the literature[6,7,12] and involves the same basic steps as small scale production except for soluble protein concentration and drying of by-product. The basic steps of production are grinding, cooking, saccharafication, fermentation, distillation, and dehydration. The first step in the process is grinding of the corn to expose starch for the cooking step. Water and enzymes (i.e. alpha amylase) are added to the milled corn for the cooking or liquification step. In this step, the starch in the corn slurry is converted into soluble high molecular weight sugars called dextrins by heat and enzymatic action. This process can be carried out in either batch or continuous flow cookers at high or low pressures. High pressure cooking has the advantages of increased conversion and considerably shorter cooking times, but much more elaborate equipment is required and is generally used only for large scale processing. The temperatures and steam pressures used range from 250°F at 15 pounds pressure for 15 minutes to 360°F at 160 pounds pressure for 30 seconds.[15] Low pressure batch cooking was used for this study for reasons of cost and practicality. The next step in the process is the saccharification step which converts the non-fermentable dextrin sugars into fermentable sugars. This is done while the slurry is still hot from the cooking step with a glucoamylase enzyme. The slurry is held at 135 - 140°F only long enough to permit a portion of the dextrins to be converted, then the mixture is cooled to fermentation temperature of 85 - 90°F. This fermentation process may be initiated as soon as sufficient sugars are available to support a yeast population. In the fermentation step, yeasts convert the sugar into ethanol and carbon dioxide. The time required for the completion of fermentation is dependent upon the strain of yeast used, but the average time required is 48 hours. All equipment currently being marketed utilizes a batch fermentation process, as was used for this study. Continuous fermentation units could allow for the use of smaller fermentation equipment and substantial reductions in production time, but complicated problems of contamination with such systems have not been solved. After completion of the batch fermentation, the ethanol is separated from the fermented slurry or beer in the distillation step. In this step, the beer is heated to vaporize the alcohol in a stripping column and the vapors are further refined in a rectifying column and cooled, and condensed to produce an azeotropic ethanol-water solution. The residue or corn stillage by-product contains the residual grain, protein, spent yeast, and water. The final step in the process is the dehydration of water extraction from the ethanol-water azeotrope to produce the anhydrous ethanol product. This process can be performed with either a hydrocarbon solvent distillation or a water absorbing molecular sieve. This overall ethanol production process uses corn, water, heat, enzymes, and yeast to produce anhydrous ethanol to be used as a fuel, and corn stillage to be used as a livestock feed.

A. Scenario I Process: Farm Production of Anhydrous Ethanol

In Scenario I, the process of producing anhydrous ethanol is carried out entirely on the farm, as illustrated in Figure 1. All required processing equipment is itemized in Table B1 of Appendix B. The corn is grown, dried, stored, and milled on the farm. The milled corn, together with water, is added to a 6,000 gallon batch cooker. The starch is converted to glucose with enzymes. This process takes four to eight hours, depending on the corn and enzymes used. The resultant slurry is then transferred to one of four 6,000 gallon fermentation tanks, with yeast, to be fermented for 48 hours. Four fermenters are used so that one tank will always be empty for proper cleaning. The cooker is also cleaned and prepared for another cycle, which is run every 24 hours. These maintenance schedules are essential in combatting contamination which is a major problem with batch fermentations. After 48 hours of fermentation, the beer is distilled in a sieve tray stripping column and a packed rectifying column to produce a 95 volume % ethanol-water azeotrope. A sieve tray stripping column is used so that the solids in the fermented beer can be run through the column. The solids are run through the stripping column to reduce ethanol losses which occur if the solids are separated before distillation. A packed rectifying

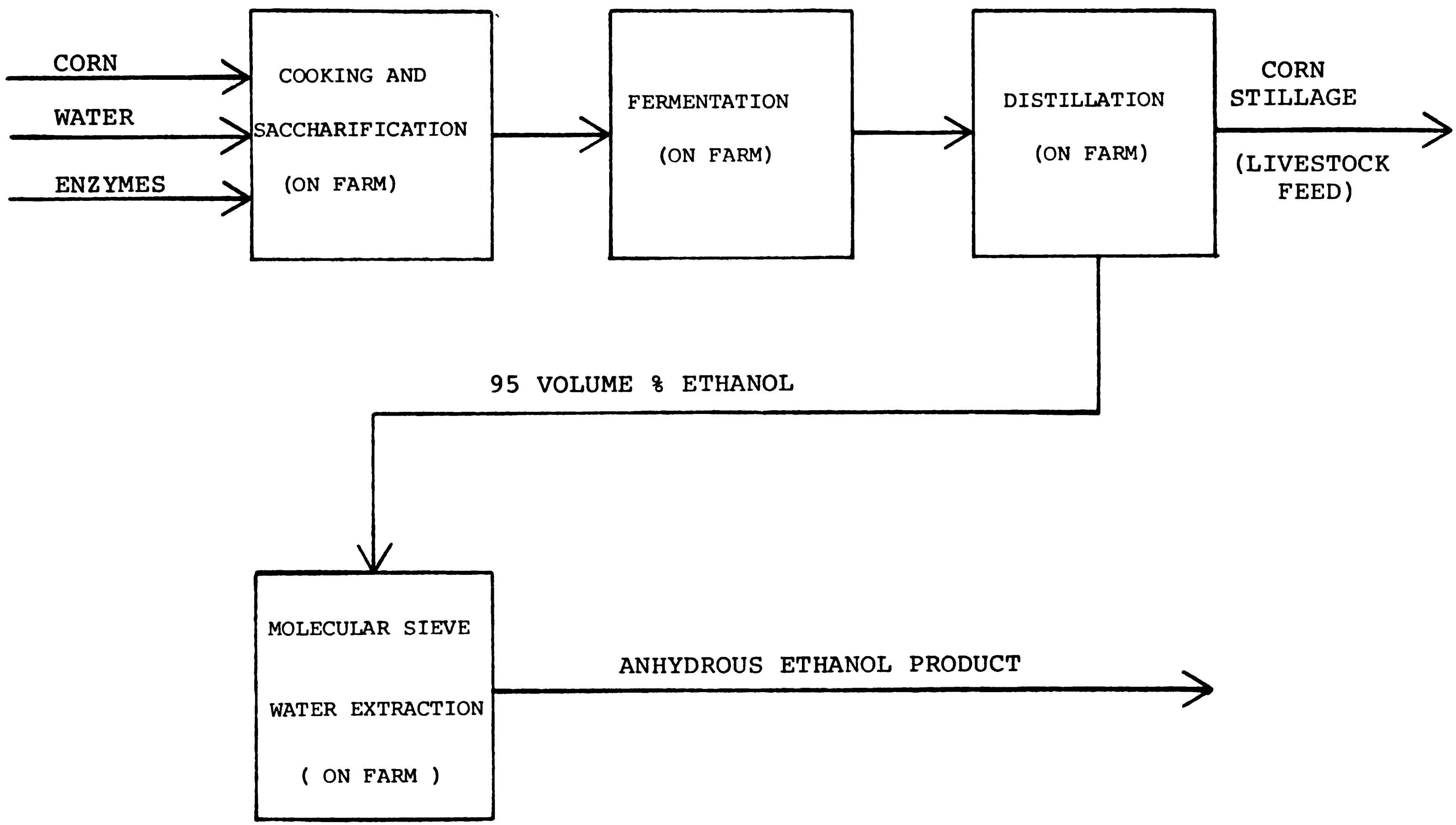


Figure 1. Scenario I Process

column is used for easier operation and control and lower capital cost. The 5% water in the azeotrope is then extracted with a regenerative molecular sieve column to obtain the anhydrous ethanol product. Azeotropic distillation with benzene solvent is the most common method for water removal from an ethanol-water azeotrope, but is not practical for this small scale facility. Benzene is a hazardous chemical which requires strict controls for safety. The benzene process requires much more equipment, labor, and capital investment and is a higher technology process than the molecular sieve process. One disadvantage of the molecular sieve process is that it requires more energy to operate than benzene-azeotropic distillation, but electricity can be used as the heat source which is also more practical than steam on a small scale farm process. The wet corn stillage by-product from the beer distillation is mixed with nutrients and fillers and fed to livestock on the farm. The overall process requires only one operator per shift, primarily for batch start-ups and tank cleaning. Fermentation, distillation, and water extraction processes are fully automated and run 24 hours per day. All yield and economic calculations use 8,000 hours or 48 weeks of operation per year, leaving a reasonable amount of time for maintenance shutdowns.

Quality control of the process is performed with laboratory tests of product streams on every eight hour shift change. The laboratory work is assumed to be done by a local laboratory but no allowance is made for re-processing of contaminated ethanol.

The anhydrous ethanol product (100,000 gallons per year) is assumed to be used by farm equipment which had been converted for ethanol fuel or sold to a local retailer. It is assumed that a local gasoline distributor is willing to buy and blend the anhydrous ethanol with gasoline.

B. Scenario II Process: Centralized Azeotropic Distillation

The overall process scheme for Scenario II (Figure 2) is the same as that for Scenario I with the exception of the water extraction from the 95 volume % ethanol-water azeotrope. All required processing equipment for Scenario II is listed in Tables B2 of Appendix B. The water extraction process for the 15 farms of Scenario II is centralized into one cooperative water extraction plant. The plant, which uses the benzene-azeotropic distillation method of water removal, is equally owned and operated by the 15 farms that use the facility. This change in processing not only uses less energy than Scenario I by using the more efficient large scale plant, but also simplifies the small scale processing for the farmer. The large scale cooperative facility can also produce a more consistent and pure product with extensive equipment and process controls and thorough product analysis

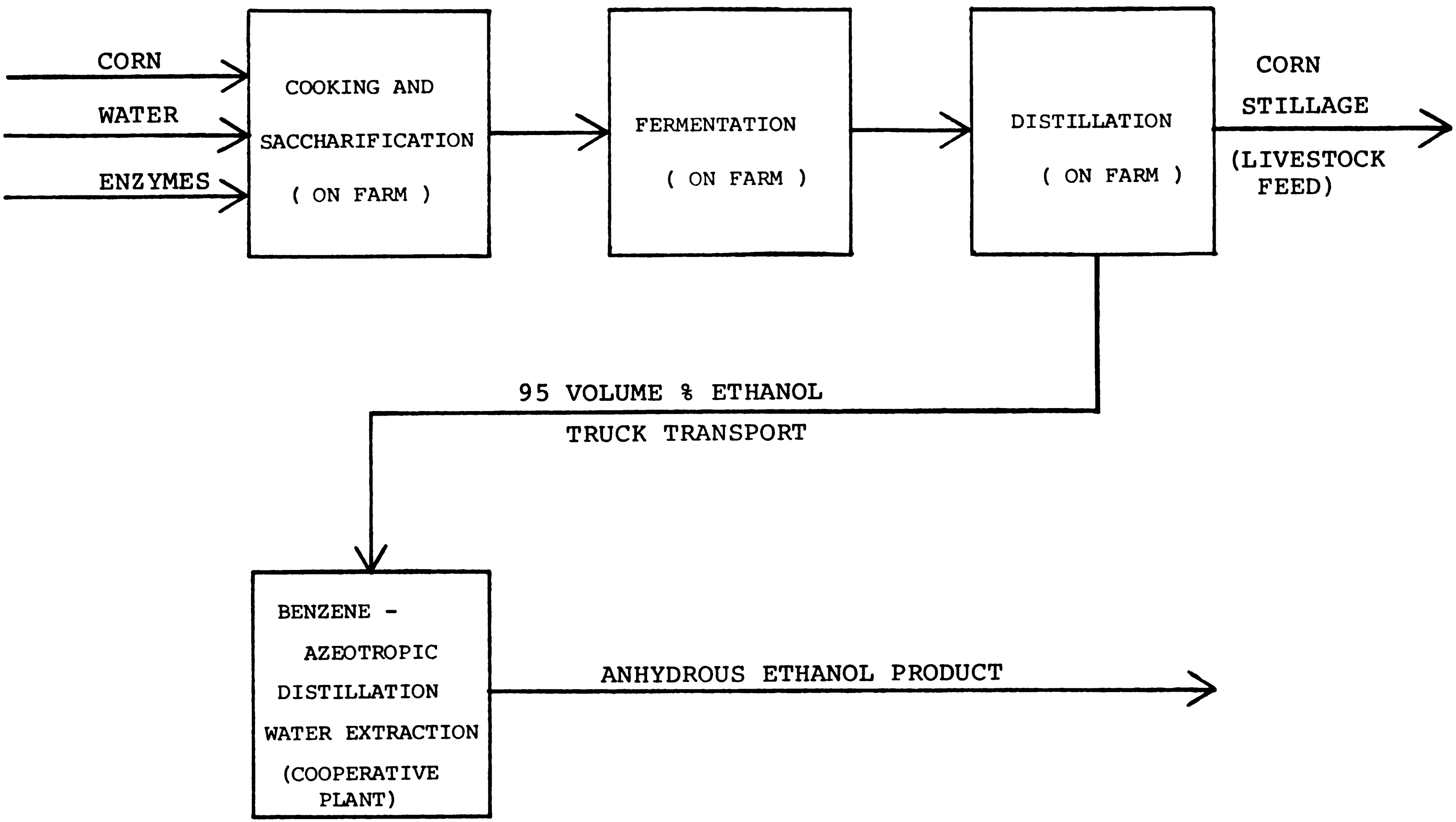


Figure 2. Scenario II Process

which is not practical or even possible with small scale production. This is an important factor in fermentation ethanol production because of possible acetic acid contamination of the anhydrous ethanol product which can occur with improper process operation.

The 95 volume % ethanol-water azeotrope is hauled by tanker truck from the producing farms, each of which produces 100,000 gallons of ethanol per year on an anhydrous basis, to the centrally-located plant. The water is removed from the ethanol-water azeotrope with azeotropic distillation using benzene as a solvent. The process requires the use of three atmospheric pressure distillation columns and a two-phase liquid separator or decanter, as listed in Table B2 of Appendix B. The anhydrous ethanol product is then trucked back to the farms after the process is completed to be used or sold to local farmers for fuel. An average distance of 30 miles between each farm and the plant is used for energy consumption calculations, which is the average distribution of farms of this size in the Saginaw Valley area.[10]

C. Scenario III Process: Centralized Ethanol Rectification and Azeotropic Distillation

The process scheme for Scenario III (Figure 3) is identical to Scenario II except for the centralization of the rectification distillation process, which is performed

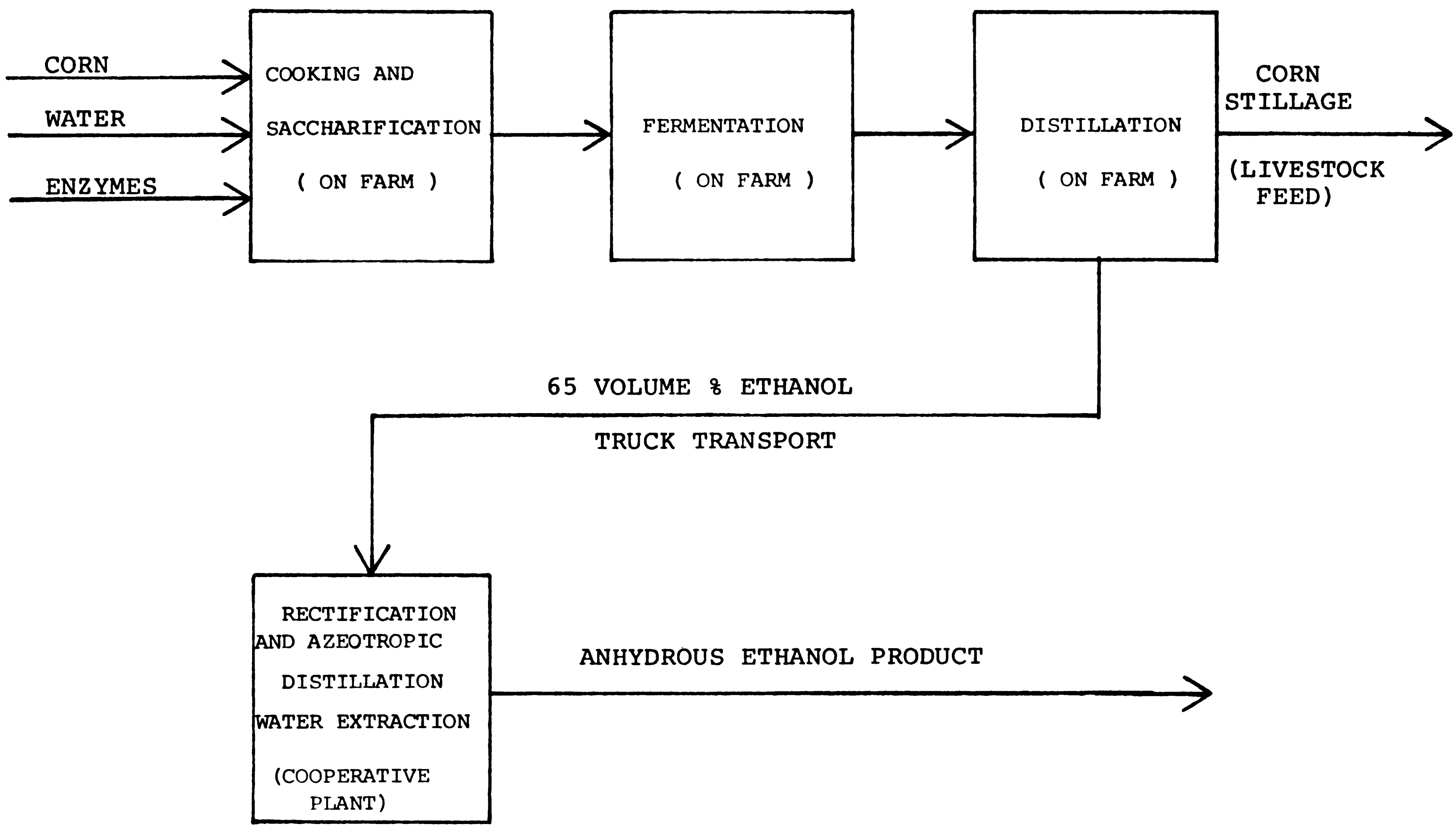


Figure 3. Scenario III Process

on the farm site in Scenarios I and II. All required equipment for this process is listed in Table B3 of Appendix B. The distillation process on the farm is changed to a simple stripping column which produces a low-grade product (65 volume % ethanol). This low-grade product is then trucked to the cooperative plant and distilled in a rectifying column which produces a 95 volume % ethanol azeotrope. The water is extracted from the azeotrope with the same benzene-azeotropic distillation process used in Scenario II. The anhydrous ethanol produced by this distillation is then trucked back to the producing farms.

This process change simplifies the small scale processing by moving the rectification portion of the distillation process from the small scale farm units to the centralized large scale plant. By making this change, the stripping of the fermented beer is the only distillation process carried out on the farm. This stripping process is far less complicated and easier to control than both a stripping and rectifying column as used in Scenario I and II. Simplification of farm processing is considered favorable by most farmers even if energy and economic savings are not realized, as illustrated by dairy farmers with the centralization of milk processing. This process change is also suggested for its possible energy and economic savings resulting from increased efficiencies of large scale processing.

III. SCENARIO ENERGY BALANCES

The energy balances around each scenario process are performed in several different ways, as illustrated in Figures 4 - 6. The energy contained in the corn feed is listed both as (a.) the energy required to grow the corn, and (b.) the energy obtainable if the corn is burned. The energy contained in the corn stillage by-product is also given two values of energy content, both of which represent the energy required to replace the protein in the by-product as an animal feed. One value (c.) includes the soluble protein when all the by-product is used and the other value (d.) neglects soluble proteins to be used if the by-product is dewatered by screening before use. These two sets of energy content values are used so that the reader may choose the parameters or values which fit specific cases of interest. The author favors the (a.) and (c.) assumptions because the values fit the conditions of the corn and stillage used in this study.

The actual measuring of energy efficiency of a process is done with an energy efficiency ratio. The energy efficiency of a process is equal to the energy output of that process divided by the energy put into that process.

All efficiency values of the scenarios are listed in Table 2.

The energy data from the energy balances are used directly for the efficiency calculations which give several different ways of measuring efficiency. The efficiency values used are the process fuel energy efficiency, from the fuel energy balance of the conversion process, and the overall energy efficiency. The process fuel energy efficiency is equal to the total fuel energy produced in ethanol divided by the total fuel energy input in coal and electricity to produce the ethanol. This figure does not include energy used to grow corn.

$$\text{Process Fuel Energy Efficiency} = \frac{\text{Total Energy In Ethanol Produced}}{\text{Total Energy in Coal and Electricity to Produce Ethanol}}$$

The overall energy efficiency is equal to the ratio of the total output energy of corn stillage and ethanol divided by the total input energy of coal, electricity, and corn.

$$\text{Overall Energy Efficiency} = \frac{\text{Total Energy In Corn Stillage And Ethanol Produced}}{\text{Total Energy Input of Coal, Electricity, And Corn}}$$

The overall energy efficiency, like the overall energy balance, is calculated in four different ways for reader convenience in Table 2.

$$\text{Overall Energy Efficiency} = \frac{\text{Total Energy In Corn Stillage And Ethanol Produced}}{\text{Total Energy Input of Coal, Electricity, And Corn}}$$

The overall energy efficiency, like the overall energy balance, is calculated in four different ways for reader convenience in Table 2.

Table 2. Scenaior Energy Efficiencies

Efficiency Type	Efficiency Scenario I	 Scenario II	 Scenario III
Process Fuel Energy Efficiency	0.645	0.650	0.683
Overall Energy Efficency			
(a, c)	0.662	0.667	0.694
(a, d)	0.585	0.592	0.613
(b, c)	0.415	0.417	0.427
(b, d)	0.366	0.368	0.376

[a] Energy required to grow corn.(12)

[b] Energy obtainable from corn if used as fuel.(11)

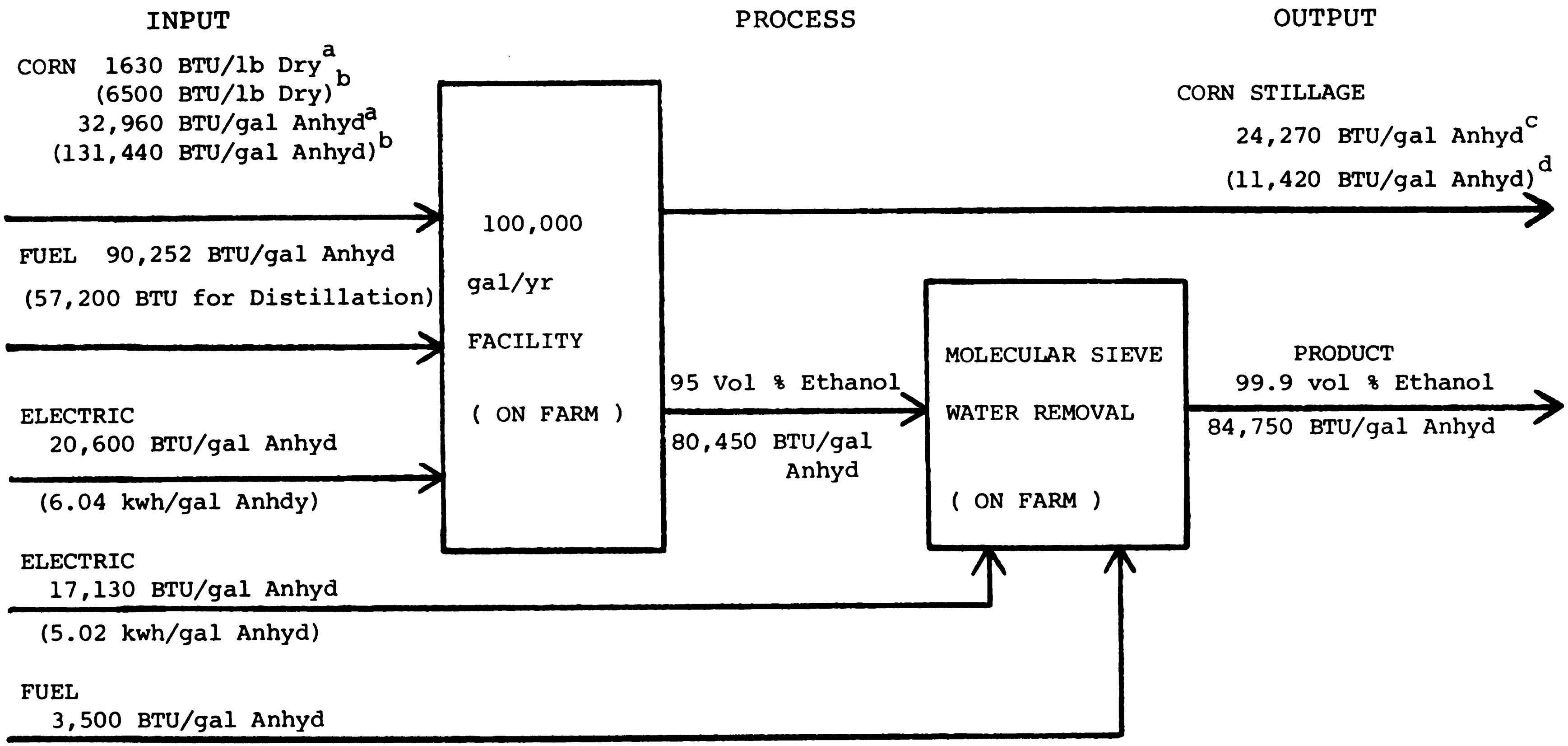
[c] Whole stillage - Energy required to replace protein as animal feed.(12)

[d] Without Solubles - Energy required to replace protein as animal feed.(12)

A. Scenario I: Energy Balance

The overall energy balance for Scenario I is given in Figure 4. The fuel requirement for azeotrope production of 90,252 BTU/gallon anhydrous ethanol is the amount of coal energy required to produce steam for the cooking of the corn, fermentation, and distillation to azeotrope. The fuel consumption for water removal of 3,500 BTU/gallon anhydrous ethanol is to assist in heating the molecular sieves for regeneration. The electric requirement to produce the ethanol-water azeotrope of 20,600 BTU/gallon anhydrous ethanol is used for pumps, fermentation agitation, fan condenser, and fermentation coolers, corn and by-product conveyers, controls, and other miscellaneous equipment. The electric requirements for the water removal section of 17,130 BTU/gallon anhydrous is primarily for heating and molecular sieves and the gaseous nitrogen which is passed through the sieves to remove the water.

All efficiency values are given on Table 2. The process fuel energy efficiency, which is the energy of the anhydrous ethanol divided by the total fuel and electric energy required to produce that ethanol is 0.645 for this case. This value shows that more fuel energy is put into the process than is produced in ethanol. The overall energy efficiency which takes the energy content of the corn fed into the process and the corn stillage by-product



[a] Energy required to grow corn.(12)

[b] Energy Obtainable from corn if used as fuel.(11)

[c] Whole Stillage - Energy required to replace protein as feed.(12)

[d] Without Solubles - Energy required to replace protein as feed.(12)

Figure 4. Energy Balance Of Scenario I

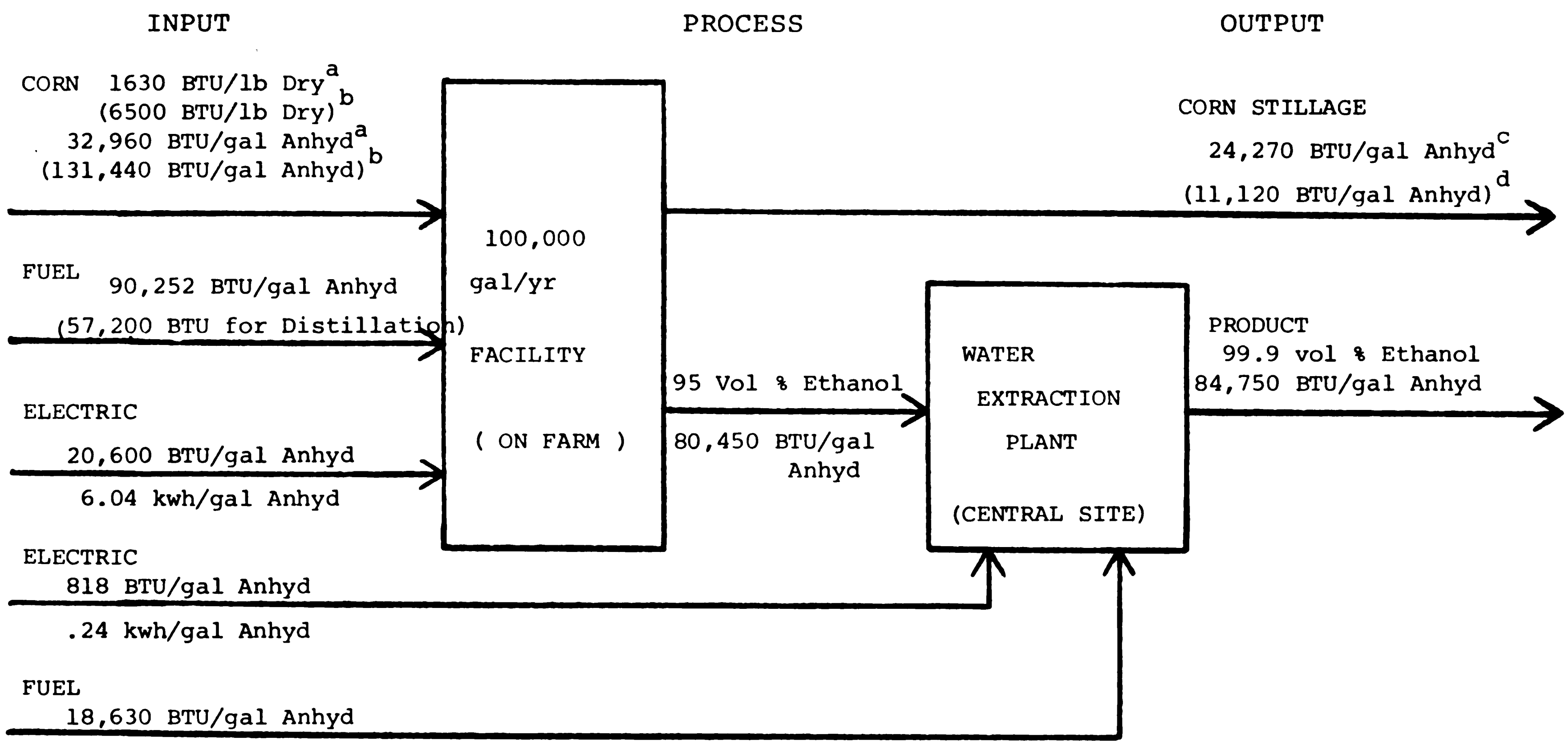
ranges from 0.662 to 0.366, depending upon the energy values chosen for the corn and by-product. This result indicates that the overall energy input is also much greater than the energy produced.

Possible energy savings could be realized with centralization of one or more of the small scale processes of the 15 farms to take advantage of large scale efficiency. Scenario II incorporates a cooperative water extraction plant to evaluate the effect of process centralization.

B. Scenario II Energy Balance

The overall energy balance for Scenario II is given in Figure 5. The corn, fuel, electric, and corn stillage energy values in producing 95 volume % ethanol azeotrope are the same as Scenario I. The total energy required to remove the water from the azeotrope is less for Scenario II because the large scale benzene process for water extraction of Scenario I. The fuel value of 18,630 BTU/gallon anhydrous ethanol for water extraction is the energy required for the three distillation columns of the process and diesel fuel for azeotrope and product transportation. The electric value of 818 BTU/gallon anhydrous ethanol is the requirement for pumps, controls, and miscellaneous uses.

The process fuel energy efficiency of 0.650 for Scenario II is a small improvement over that for Scenario



[a]Energy required to grow corn.(12)

[b]Energy obtainable from corn if used as fuel.(11)

[c]Whole Stillage- Energy required to replace protein as feed.(12)

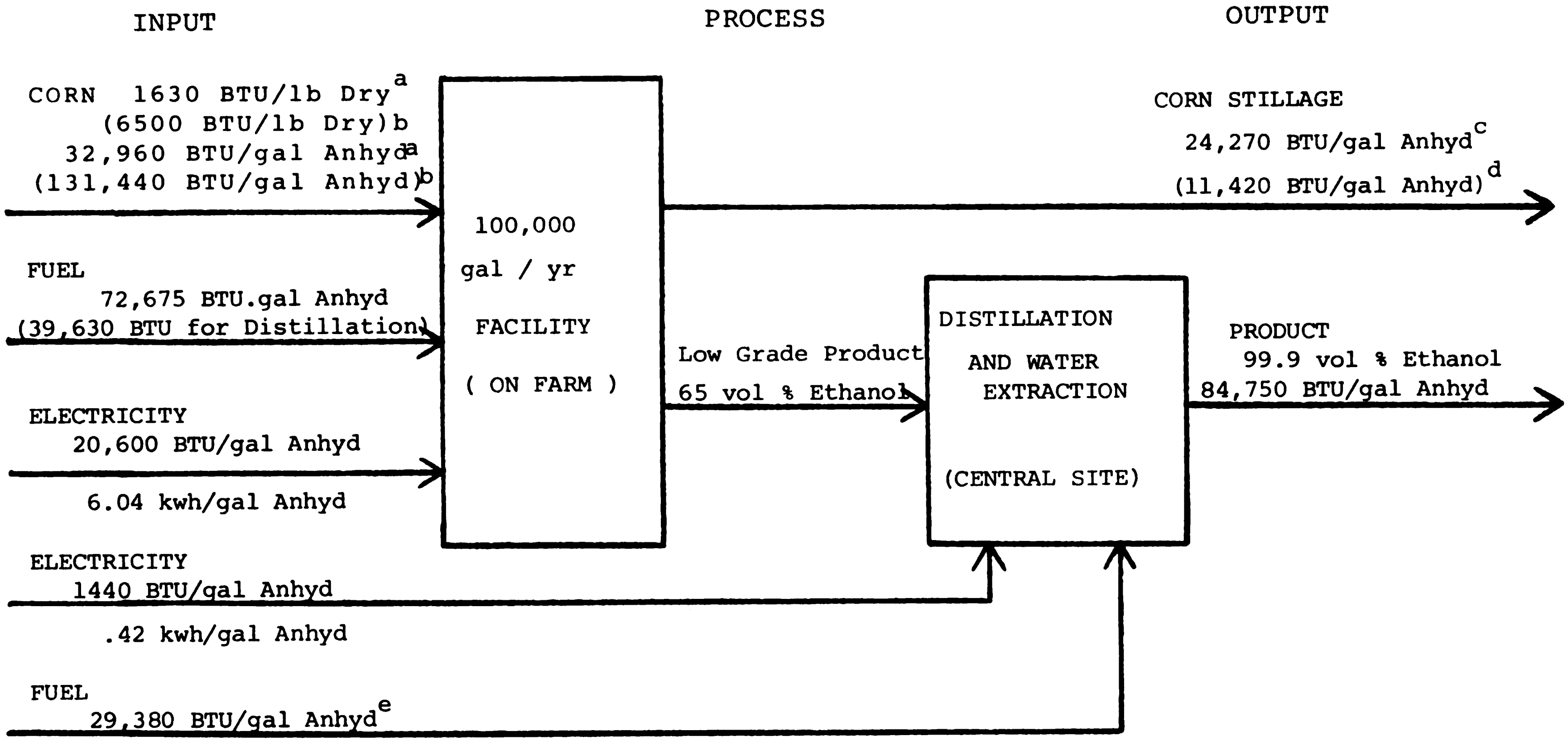
[d]Without Solubles- Energy required to replace protein as feed.(12)

Figure 5. Energy Balance of Scenario II

I of 0.645, as shown in Table 2. The overall energy efficiency range of 0.667 to 0.368 is also slightly better than that of Scenario I of 0.662 to 0.366. This increase in efficiency ratios of Scenario II over Scenario I is less than 1%, but is significant in the fact that it reveals a trend that further increases in process centralization might also further increase efficiency. Scenario III increases process centralization to test the efficiency trend by moving the ethanol rectification process to a cooperative plant together with the water extraction process.

C. Scenario III: Energy Balance

The overall energy balance for Scenario III is given in Figure 4. The corn, electric and corn stillage energy values are unchanged in this case. The fuel energy requirement for the farm facility of 72,675 BTU/gallon anhydrous ethanol is substantially lower than the 90,252 BTU/gallon anhydrous for the other cases. This reduction can be attributed to producing 65 volume % ethanol with a stripping column and transporting it to the central refinery, instead of the process used in the other scenarios, which produces a 95 volume % ethanol distilled in a stripping and rectifying column. This low grade product is distilled to 95 volume % ethanol with benzene extraction at the central distillation and extraction facility. The fuel requirement for the central facility



[a]Energy required to grow corn.(12)

[b]Energy obtainable from corn if used as a fuel.(11)

[c]Whole Stillage - Energy required to replace protein as feed.(12)

[d]Without Solubles - Energy required to replace protein as feed.(12)

[e]Estimated from "Industrial Scale" distillation.

Figure 6. Energy Balance For Scenario III

of 29,380 BTU/gallon anhydrous ethanol is used for distillation to azeotrope, diesel fuel to transport low grade 65 volume % ethanol and anhydrous product, and the three distillations required for water removal. The electric value of 1,440 BTU/gallon anhydrous ethanol is the requirement for pumps, controls, and miscellaneous uses.

The process fuel energy efficiency of 0.683, as well as the overall energy efficiency range of 0.694 to 0.376 are 5% to 6% better than those of either of the other scenarios, which is significant. These efficiency increases can be attributed to the production of 65 volume % ethanol on the farm and refining done at a large scale facility. The large scale facility can distill the low grade (65 volume %) ethanol to azeotrope (95 volume %) transport required. This scenario energy study clearly illustrates the energy savings which can be realized with incorporation of large scale processes with small scale fermentation ethanol production.

Further process centralization of small scale processes is not considered since both fermented beer and corn stillage by-product would have to be transported if the entire distillation process was centralized. It would require less energy to transport the corn, instead of the fermented beer (corn and water), to the cooperative facility for fermentation and distillation, and then haul the corn stillage by-product back to the farm. But this large amount of process centralization is actually a large scale production facility producing a wet by-product (corn stillage) which has been previously studied in the literature.[6,7,12]

Two other possible opportunities for energy reduction are the use of high moisture corn over dried corn and an extruder for cooking instead of batch cooking. High moisture corn could save up to 3,000 BTU per gallon of anhydrous ethanol in process energy normally used to dry corn. An extruder could save up to 11,000 BTU per gallon of anhydrous ethanol in cooking and saccharification requirements. An extruder runs on electricity which also makes it practical for small scale work. The energy reductions result in a process fuel efficiency of 0.749 (7% increase over Scenario III) is a significant increase. These methods were not used for this study because of a lack of required yield and conversion data, but is recommended for small scale production because of possible energy reductions.

IV. ECONOMIC ANALYSIS

The economic evaluation of the three scenarios is based on the economics of one farm, out of the 15 in each scenario, with each farm owning an equal share of any co-operative facilities used. All economic assumptions used in the scenarios are listed on Table 3. Capital investment is assumed to be borrowed on a ten year loan at 15% interest and depreciated on a straight scale over ten years with no salvage credit. No profit on capital investment is taken by the farmers or the cooperative. Corn is priced at \$2.70 per bushel, electricity at \$.032 per kilowatt-hour, and coal at \$40 per ton. Operators for the farm and cooperative facilities are paid \$15,000 per year for a 40-hour work week. The total capital investment is calculated using the equipment cost as a basis together with a standard factor method for installation costs, contingency and miscellaneous costs, and engineering and licensing costs. Installation costs are 38% of equipment cost, contingency and miscellaneous costs are 18% of equipment cost, and engineering and licensing costs are 12% of equipment cost. These values represent commercial rates using new equipment. Used equipment could lower equipment costs and home installation could

Table 3. Economic Assumptions

Capital Investment: Ten Year Loan @ 15% Interest

Profit: No Profit on Capital Investment

Overall Investment: 1980 Cost Basis

Facility Amortization Period: 10 Years

Corn Costs: $2.70 per Bushel (56 lbs @ 15.5% moisture)

Fuel Source: Coal @ $40 per Ton

Electricity: Purchased @ $.032 per Kilowatt-Hour

Labor: $15,000 per Worker per Year

Installation: 38% of Equipment Cost

Contingency and Miscellaneous: 18% of Equipment Cost

Engineering and Licensing: 12% of Equipment Cost

Depreciation: 10 Year Straight Scale with No Salvage Credit lower installation costs. The overall economics of each scenario, including capital investment, operating expenses, and all miscellaneous expenditures, are given on a 1980 cost basis.

The market for ethanol is assumed to be local and used for either farm equipment, which has been converted to use ethanol as a fuel, or sold to a local gasoline blender or retailer. The corn stillage by-product is also used locally by farmers for livestock feed, but feeding facilities are restricted to the producing farm because of stillage handling problems. All stillage, including solubles, is used as feed and is given a credit of $43 per ton at 30% moisture.[11] The anhydrous ethanol is given the price required to cover operating costs and the capital investment loan payments with no profits.

A. <u>Scenario I: Economics</u>

The total capital investment for Scenario I is itemized in Table 4. The equipment cost of $330,750 is for all equipment for on-farm production as listed in Table C1 in Appendix C. The cost of installing the equipment is 38% of the equipment cost, or $125,100. Contingency and miscellaneous costs are 18% of equipment cost ($59,100) and engineering, licensing, and permits are 12% of equipment cost ($40,000). The total of these values or total capital investment is $554,950 per farm. The total capital investment is paid off by a ten year loan at 15% interest which amounts to annual payments of $110,575, as shown in Table 5 which itemizes the overall economies of Scenario I. The total capital investment is depreciated on a ten year straight scale or $55,495 annually. The annual operating cost is $263,205, of which the price of corn ($115,385), energy($62,300), and labor($45,000), are the major contributors, as shown in Table C4 in Appendix C. The total annual cost of a small scale facility in Scenario I is $413,747, which includes a by-product credit of $15,528, as listed in Table 5. With the production of 100,000 gallons of anhydrous ethanol per year, the resultant cost of producing anhydrous ethanol is $4.14 per gallon.

The major cause of this high cost of production (market value of anhydrous ethanol is $1.98 per gallon)[14] is the corn, energy, and labor costs. The corn cost of

Table 4. Total Capital Investment

A. Scenario I		
Equipment Cost	$330,750	
Installation	125,100	
Contingency and Misc.	59,100	
Engineering, Licenses, Permits, Etc.	40,000	
TOTAL CAPITAL INVESTMENT PER FARM	$110,575	
Annual Capital Investment Loan Charge Per Farm (10 Year Loan at 15% Interest)	$110,575	
B. Scenario II		
i. Farm Facility		
Equipment Cost	$296,350	
Installation	112,090	
Contingency and Misc.	52,900	
Engineering, Licenses, Permits, Etc.	35,800	
TOTAL FARM INVESTMENT	$497,140	(y)
ii. Water Extraction Plant		
Equipment Cost	$487,700	
Installation	184,500	
Land (2 acres farmland)	10,000	
Contingency and Misc.	87,060	
Engineering, Licenses, Permits, Etc.	58,900	
TOTAL PLANT INVESTMENT	$828,160	
Plant Investment Per Farm (15 Farms Per Cooperative)	$ 55,210	(z)
TOTAL CAPITAL INVESTMENT PER FARM	$552,350	(y+z)
Annual Capital Investment Loan Charge Per Farm (10 Year Loan at 15% Interest)	$110,056	

Table 4. (Continued)

C. Scenario III

i. Farm Facility

Equipment Cost	$263,750	
Installation	99,780	
Contingency and Misc.	47,100	
Engineering, Licenses, Permits, Etc.	31,900	
TOTAL FARM INVESTMENT	$442,530	(y)

ii. Distillation And Water Extraction Plant

Equipment Cost	$571,200	
Installation	216,100	
Land (2 acres farmland)	10,000	
Contingency and Misc.	101,970	
Engineering, Licenses, Permits, Etc.	68,980	
TOTAL PLANT INVESTMENT	$968,250	
Plant Investment Per Farm (15 Farms Per Cooperative)	$ 64,550	(z)
TOTAL CAPITAL INVESTMENT PER FARM	$507,080	(y+z)
Annual Capital Investment Loan Per Farm (10 Year Loan At 15% Interest)	$101,040	

Table 5. Summary of Overall Economics

A. Scenario I

	Annual Cost	$/Gal. Anhyd.
Corn	$115,385	$1.15
Labor	45,000	.45
Coal	26,900	.27
Electric	35,400	.35
Miscellaneous	40,520	.41
Capital Investment (10 Yr. Loan @ 15%)	110,575	1.11
Ten Year Depreciation	55,495	.56
By-Product Credit (43/ Ton @ 30% Moisture)	-15,528	-.16
NET COST:	$413,747	$4.14

B. Scenario II

	Annual Cost	$/Gal. Anhyd.
Corn	$115,385	$1.15
Labor	53,000	.53
Coal	26,280	.26
Electric	20,082	.20
Miscellaneous	32,381	.32
Capital Investment (10 Yr. Loan @ 15%)	110,056	1.10
Ten Year Depreciation	55,235	.55
By-Product Credit ($43/ Ton @ 30% Moisture)	-15,528	-.16
NET COST:	$394,891	$3.95

C. Scenario III

	Annual Cost	$/Gal. Anhyd.
Corn	$115,385	$1.15
Labor	53,000	.53
Coal	21,056	.21
Electric	20,346	.20
Miscellaneous	31,286	.31
Capital Investment (10 Yr. Loan @ 15%)	101,040	1.01
Ten Year Depreciation	50,708	.51
By-Product Credit ($43/ Ton @ 30% Moisture)	-15,528	-.16
NET COST:	$377,476	$3.77

$1.15 per gallon of anhydrous ethanol (abbreviated: PGAE) is a large portion of the ethanol cost, but is reasonable compared to the cost of corn for large scale (5 million gallons per year) production of $1.04 PGAE considering the higher ethanol yields achieved with large scale production.[12] But the energy costs ($.62 PGAE) and labor costs ($.45 PGAE) is considerably higher than the energy costs ($.41 PGAE) and labor costs ($.21 PGAE) for large scale production.

Possible reductions in equipment and operating costs could be achieved with process centralization. Large scale cooperative processes have advantages of scale up equipment, cost savings and lower operating cost from greater efficiency. Scenario II uses a cooperative large scale water extraction plant to find the economic savings of process centralization.

B. Scenario II: Economics

The total capital investment for Scenario II is itemized in Table 4. The summary of all costs and credits of the overall economics of Scenario II, including the total capital investment, depreciation, operating cost, and by-product credit is listed in Table 5. The total cost for one farm in Scenario II to produce ethanol for one year, from Table 5, is $394,891 or $3.94 per gallon of anhydrous ethanol (PGAE), which is less than that for Scenario I of $4.14 PGAE. This reduction is primarily due to the lower annual operating costs of Scenario II of $245,128 (including 1/15 of the operating costs of the cooperative plant) compared to $263,205 per year for Scenario I. This operating cost reduction can be attributed to the energy savings in Scenario II resulting in lower energy costs. The annual energy costs (electric and coal) are $46,362 compared to $62,300 for Scenario I. This energy cost in terms of gallons anhydrous ethanol produced is $.46 PGAE for Scenario II, which is substantially closer to the large scale value of $.37 PGAE than Scenario I ($.62 PGAE). This reduction in energy costs is due to the use of the more efficient large scale water extraction plant. Equipment, corn, and labor costs are essentially the same as in Scenario I, as shown in Table 5. Scenario III increases utilization of large scale facilities by centralizing the rectification mode of distillation.

C. Scenario III: Economics

An itemized list of investments for Scenario III together with the total capital investment is given in Table 4. The overall economics of Scenario III is listed in Table 5. The total annual cost of ethanol production for one farm in Scenario III is $377,476 or $3.77 per gallon of anhydrous ethanol (PGAE). This is lower than the total cost value for Scenario II of $3.94 PGAE. This reduction is due to slightly lower energy costs and reduced capital costs. The capital investment loan payment reduction of $9,000 per year or $.09 PGAE over Scenario II is from scale-up savings in adding more large scale central processing to Scenario III. The energy savings can also be attributed to the addition of the more efficient large scale processing. The energy costs for Scenario III is $42,056 per year or $.42 PGAE. This value is surprisingly close to the energy cost of $.37 for large scale production,[12] for an overall process which has a substantial amount of small scale processing.

V. SUMMARY OF RESULTS AND RECOMMENDATIONS

Three scenarios for small scale ethanol production, 100,000 gallons of anhydrous ethanol per year per farm, were studied to evaluate and compare the energy and economic requirements of each case to those of large scale industrial production. The summary of the overall process requirements and costs for each scenario compared to the industrial scale case, 5 million gallons of anhydrous ethanol per year, is given in Table 6. The comparison of energy efficiencies and production costs of the small scale production schemes to industrial scale production is listed in Table 7.

The production of anhydrous ethanol from corn with small scale processing entirely on a corn-producing farm (Scenario I) is the least favorable production scheme of the three schemes studied. Scenario I can produce ethanol for $4.14 per gallon of anhydrous ethanol and has a process fuel efficiency of 0.645 (BTU out/BTU in) and an overall fuel efficiency of 0.662.

The small scale production of anhydrous ethanol utilizing a centralized large scale water extraction plant (Scenario II) can produce ethanol for $3.95 per gallon of anhydrous ethanol. Scenario II also has a fuel energy

Table 6. Summary of Process Requirements and Costs: Farm-Scale vs. Industrial Scale Ethanol Production.

	Scenario I: Farm Production of Anhydrous Ethanol		Scenario II: Centralized Azeotropic Distillation		Scenario III: Centralized Ethanol Rectification and Azeotropic Distillation		Industrial Scale(12)	
	Consumption Per Gallon Product	Cost Per Gallon Product	Consumption Per Gallon Product	Cost Per Gallon Product	Consumption Per Gallon Product	Cost Per Gallon Product	Consumption Per Gallon Product	Cost Per Gallon Product
Corn[a]	.43 bu	$1.15	.43 bu	$1.15	.43 bu	$1.15	.40 bu	$1.04
By-Product Credit[b]	6.39 lbs dry	$ .16	6.39 lbs dry	$ .16	6.39 lbs dry	$ .16	6.12 bus dry	$ .48
Coal[c]	13.46 lbs	$ .27	13.14 lbs	$ .26	10.85 lbs	$ .21	12.67 lbs	$ .24
Electric[d]	11.05 kwh	$ .35	6.26 kwh	$ .20	6.28 kwh	$ .20	4.20 kwh	$ .13
Labor[e]	.062 hr	$ .45	.073 hr	$ .53	.073 hr	$ .53	.039 hr	$ .21
Miscellaneous Production and Operating Costs[f]	--	$ .41	--	$ .32	--	$ .31	--	$ .24
Capital Charges[g]	--	$1.11	--	$1.10	--	$1.02	--	$ .40
Depreciation[h]	--	$ .56	--	$ .55	--	$ .51	--	$ .20
Anhydrous Ethanol		$4.14		$3.95		$3.77		$1.98

[a]$2.70 per bushel @ 56 lbs. and 15.5% moisture.

[b]$43 per ton for 30% moisture by-product for small scale production.(11) $140 per ton for 10% moisture by-product for industrial scale production.(12)

[c]$40 per ton.

[d]$.032 per kilowatt-hour.

[e]$15,000 per operator per year.

[f]Costs include enzymes, yeast, water, water treatment, taxes, insurance, and maintenance.

[g]Annual loan charge @ 15% interest for equipment costs, installation, engineering, licensing, and other miscellaneous capital costs.

[h]10 year straight scale with no salvage credit.

Table 7. Comparison of Energy Efficiencies (Outputs/Inputs) and Production Costs for Farm Scale to Industrial Scale Ethanol Production.

	Scenario I: Farm Production of Anhydrous Ethanol	Scenario II: Centralized Azeotropic Distillation	Scenario III: Cenralized Ethanol Rectification And Azeotropic Distillation	Industrial Scale(12)
Process Fuel[a] Efficiency	0.645	0.650	0.683	0.505-0.820
Overall Efficiency[b]	0.662	0.667	0.694	0.812-1.130
Production Cost ($ Per Gallon of Anhydrous Ethanol)	$4.14	$3.95	$3.77	$1.98

[a]Total energy in ethanol produced divided by the total energy in process fuel to produce the ethanol.

[b]Using energy required to grow corn for corn energy value and energy required to replace protein as animal feed for corn by-product energy value.

efficiency of 0.650 and an overall energy efficiency of 0.667. Both the efficiency and the ethanol selling price are better than those of Scenario I because of the addition of a more efficient centralized large scale process.

The best of the three scenarios for small scale fermentation ethanol production from corn, both economically and energetically, is Scenario III. This scheme produces low grade ethanol entirely on the farm (65 vol %) by stripping the fermented corn beer. The stripped stillage is then fed to livestock on the farm. The low grade product is then trucked to a centrally-located cooperative plant for anhydrous ethanol production. The energy and economic savings in this scenario results from the greater use of efficient large scale facilities over the other two scenarios, where more processing is done with less efficient small scale facilities on the farm. The resultant ethanol selling price for Scenario III is $3.77 per gallon anhydrous ethanol. Scenario III also has an overall energy efficiency of 0.694 and an overall process fuel efficiency of 0.683. Both the ethanol price and the efficiency values are the best of the three scenarios, but they are not competitive with commercial scale costs and energy usage. The current market value of anhydrous ethanol is $1.98 per gallon[14] and most large scale commercial processes have efficiencies close to unity.[12] These results show that small scale production of ethanol to be economically and energetically unfavorable compared to large scale production.

The operating costs ($2.41 per gallon of anhydrous ethanol) are one of the major causes of the high price of ethanol in Scenario III. The price of corn $1.15 per gallon of anhydrous ethanol at $2.70 per bushel) is one reason for these high operating costs and can only be lowered with increased yields of ethanol per bushel. Yields would be difficult to improve over the value used in this study (2.34 gallons anhydrous ethanol per bushel of corn) with small scale batch fermentation since the value used was obtained under carefully controlled experimental conditions.

Overall operating and equipment cost could be reduced if continuous fermentation processes were perfected. Continuous fermentation would allow for smaller fermentation equipment and substantial reductions in production time, but complicated problems of contamination with such systems have not been solved. A breakthrough in this area could vastly improve the overall economics of small and large scale fermentation ethanol production. Operating costs might be further reduced by using wood, corn stalks, or some other farm residue for fuel to produce steam.

Labor and energy costs are also responsible for the high ethanol price in small scale production. Labor costs ($.53 per gallon of anhydrous ethanol) are very high with respect to large scale production labor costs ($.21 per gallon anhydrous ethanol for a 5 million gallon per year plant).[12] This value could possible be reduced with further process centralization or increased process automation. Energy costs of Scenario III ($.42 per gallon of anhydrous ethanol) are close to large scale energy costs ($.37 per gallon of anhydrous ethanol),[12] but could be further reduced by using high moisture corn instead of drying the corn and the extruder for corn cooking and saccharification over batch processing. High moisture corn can save up to 3,000 BTU per gallon of anhydrous ethanol and an extruder up to 11,000 BTU per gallon of anhydrous ethanol. Even with these proposed savings, which decrease the price of ethanol by 1.4¢ per gallon of anhydrous, the small scale production of ethanol from corn is still not currently feasible, compared to large scale production.

The results of the overall scenario studies indicate the importance of minimizing small scale processes. Even with the centralized processes of these scenarios, small scale fermentation ethanol production from corn cannot currently compete with large scale industrial production.

APPENDICES

APPENDIX A:

DESIGN, OPERATION AND EXPERIMENTAL RESULTS OF SMALL SCALE ETHANOL PRODUCTION FACILITY

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DESIGN, OPERATION AND EXPERIMENTAL RESULTS OF SMALL SCALE ETHANOL PRODUCTION FACILITY

Distillation Column Design Basis

The distillation column has been designed using current chemical engineering techniques to meet the requirements of maximum efficiency and minimal height. The column was designed to handle a continuous feed of 8-10% ethanol solution with slurried solid byproducts. A column height of 10 feet was used to avoid the requirements of a tall containment building. This small size was obtained by using the column only as a stripping column (no reflux) for the initial beer feed. If a product over 65 vol % ethanol was required, the product could be further purified by using the same column in a separate distillation step as a rectifying column. This procedure can also save energy since the energy costs of producing ethanol increase with increasing reflux.

Stainless steel sieve tray plates with downcomers were used for their ability to handle slurries and resistance to ethanol corrosion. Steam coils were used for the heat source instead of steam injection because of the energy savings and no byproduct dilution. The vapor condenser was cooled with well water which was recycled to the cooking stage of the process.

Since the distillation column was also to be used as a demonstration tool, glass externals were used. The glass column does not corrode like soft steel and was easy to disassemble for maintenance. All pipes leading to the column were either PVC plastic or stainless steel, in order to resist ethanol corrosion.

1. Design Methods

Table A1 lists the design specifications of the column. Figure A1 has a schematic diagram of the equipment. Table A2 shows the costs of the hardware purchased for the column.

The calculation of the diameter of the distillation column was done using a feed flow rate of 25 gallons per hour and 9% ethanol composition. The design capacity of the column was 8,000 gallons of anhydrous ethanol per year. The method for calculation [1,4] used the maximum allowable vapor velocity in the column as a basis which was calculated from the surface tension and the densities of the liquid and vapor. The downcomer and weir height sizings for the sieve trays were done by assuming the dimensions and then calculating the resulting flowrates and plate hydraulics (height of liquid in downcomer, height of liquid and froth on plate, etc.) to prove the design.[1] The calculated liquid and froth heights were also used to decide on the spacing between the plates.

The vapor hole sizes and downcomer collector dimensions were based upon the average size of the ground corn particles (¼ inch) being used in the process. Both the collectors and vapor holes were made large enough so the corn particles could pass through them freely. The total number of vapor holes or open area of the plates

Table A1. Pilot-Scale Distillation Column Design Specifications.

---

1. Column

    9 inch diameter column
    9 feet 5 inch overall height
    Corning glass

2. Sieve Trays

    11/32 inch vapor holes
    38 vapor holes per plate (7.28% open area)
    1¼ inch diameter downcomer
    3 inch diameter collectors
    1½ inch weir height
    9 inch spacing between plates
    10 plates in column
    Stainless steel construction

3. Reboiler

    30 feet of ½-inch copper tubing
    4 square feet heat exchange area

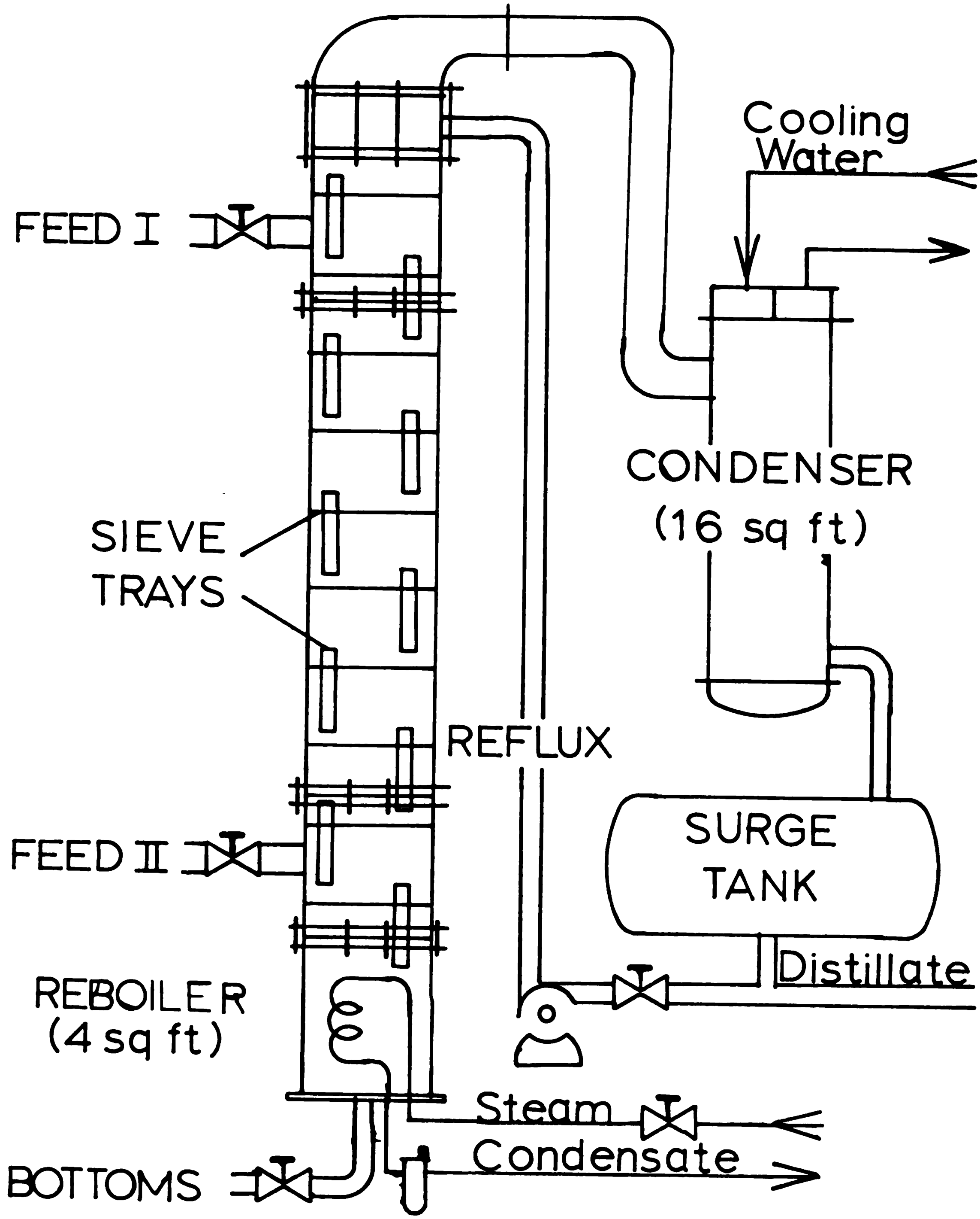
4. Condenser

    16 square feet heat exchange area
    Vapor on shell side
    Cooling water through tubes (4 pass)
    3/8 inch co-per tubes
    5 inch diameter brass shell

5. Piping

    3/4 inch feed and bottoms lines

Figure A1. Schematic Diagram of Combination Stripping - Rectification Column Design



Cooling Water
FEED I
CONDENSER (16 sq ft)
SIEVE TRAYS
REFLUX
SURGE TANK
FEED II
Distillate
REBOILER (4 sq ft)
Steam
Condensate
BOTTOMS

Table A2. Hardware for Distillation Column

# Units	Description	Cost/Unit*
1	Glass Straight Pipe 9" x 59"	$ 500.00(1)
2	Unequal Galss Tee 9" x 1.5"	270.00
1	Glass Reducing Ell 9" x 3"	247.00
1	Glass Straight Pipe 9" x 12"	278.00
1	Glass Straight Pipe 9" x 9"	220.00
6	Connecting Flange Kit 9"	98.00
6	Gaskets 9"	58.25
1	Misc. Fittings, Flanges, Gaskets	284.10
1	Condenser (Copper & Brass, 16 sq. ft.)	550.00(2)
10	Sieve Trays (Stainless) fabricated	181.30(3)
1	Column Support	634.80
1	Valves, Piping, Misc. Plumbing	980.00(4)
2	Progressive Cavity Pumps 3/4"	1,500.00
3	Plastic Storage Tanks, 250 gal.	270.00
1	Misc. (paint, lumber, etc.)	391.08

Total Distillation Cost (without assembly) = $10,375.48

*SOURCE: (1980 Prices)
1. Corning Glassware
2. American Standard
3. University Engineering Shop
4. Local Industrial Suppliers

was known from the literature[1, 5, 6, 7] to be within a range of 6-10% of the active area. An open area of 8% was chosen initially and was experimented with by plugging holes to find the optimal value for the column.

The condenser was sized to condense the vapor from 100 gallons per hour of feed to be sure it was large enough for a wide range of vapor flowrates. The reboiler was designed with a large fouling factor (100 Btu/°F-sq. ft.-hr.) because of the fouling tendency of corn mash and the low energy of available steam (<100 psig).

2. Column Controls

The operational control of the distillation column can be done by numerous methods depending on what parameters are important to the process. In this case, the complete stripping of the ethanol from the bottoms was the most important. The column controls were designed to ensure this condition. Table A3 and Figure A2 contain the control equipment and the control schematic diagram. Table A6 lists the costs of control and process monitoring equipment for the column.

Throughout most of this study, the distillation column was operated without instrument controls because of the long lead time required for their specification and delivery. Process monitors and controllers have now been installed. The column can be controlled by adjusting two parameters, which are the maximum number that can

Figure A2. Schematic Diagram of Stripping - Rectification Column Controls

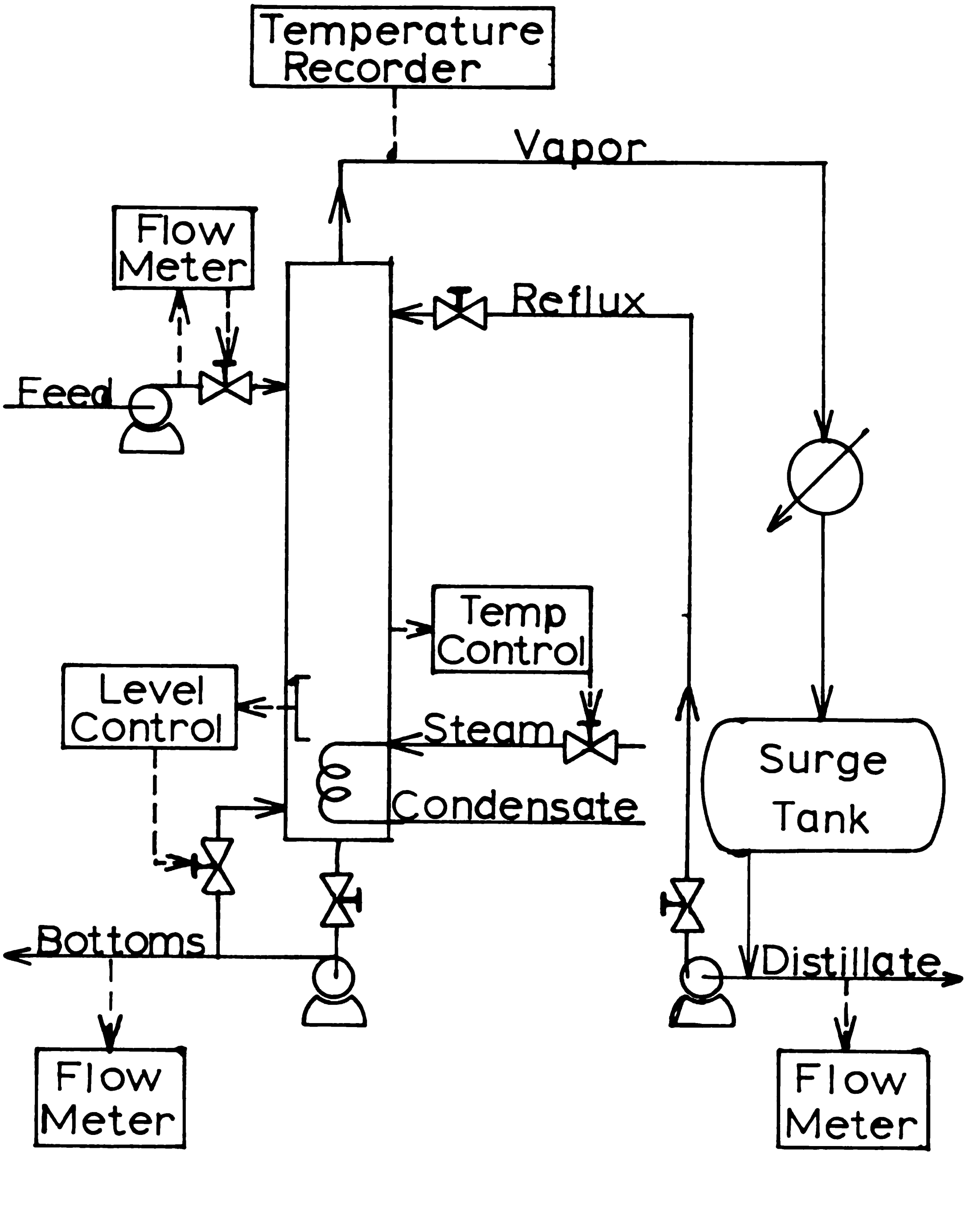

Temperature Recorder
Vapor
Flow Meter
Reflux
Feed
Temp Control
Level Control
Steam
Condensate
Surge Tank
Bottoms
Distillate
Flow Meter
Flow Meter

Table A3. Control Operations and Equipment

Operations	Equipment
Reboiler	Bottoms Control Valve
	Transducer
	Level Controller
Steam Control	Thermocouple and Transmitter
	Steam Control Valve
Constant Feed Controller	Flow Meter
	Feed Control Valve
Temperature Monitor	Thermocouples
	Recorder
Steam and Process Flow Monitors	Steam Flow Meter
	Bottoms Flow Meter
	Distillate Flow Meter
	Recorder

Table A4. Control Equipment for Distillation Columns.

Description		Price
Reboiler level control	Controller	\$1,001.00 (1)
	Transducer (Remote Seals)	1,410.00
	Control Valve 3/4"	458.00
Feed Control	Mass Flow Meter	3,225.00 (2)
	Control Valve 3/4"	458.00 (1)
Steam Control	Control Valve (air) ½"	386.00
	Thermocouple & Transmitter	850.00
Temperature Monitor	12 Point Recorder	2,095.00
	Thermocouples (12)	840.00
Flow Meters	Steam Meter & Transmitter	987.00 (3)
	Steam Flow Indicator	747.00
	Mass Flow Meter (Bottoms)	3,225.00 (2)
Total Automated Control (without installation) =		\$18,977.00

*Source: 1. Taylor Instruments
(1980 Prices) 2. Micro Motion Inc.
3. Foxboro

be controlled for this type of column. The steam flow and the bottoms flow are the controlled variables because of the large effect both have on the bottoms composition. The steam flow is controlled by temperature of the bottoms liquid and the bottoms flow controlled by the level of the liquid in the reboiler.

The feed to the column fluctuated in our system because of the decreasing level in the tank from which the feed was being pumped. The column feed should be constant since the entire column is disrupted by feed fluctuations. A flow meter and a control valve are specified for keeping the feed constant. This is not a controlled parameter (i.e., adjusted by column conditions) but only a means of reducing fluctuations in the feed.

Temperature and flowrate monitors are not crucial to column operation but are recommended for an automated system. A temperature log of the top vapor and the bottoms liquid is important for observing how well the column has been operating and serves as a check on distillate and bottoms purity. Steam and process flowmeters are less important than temperature recorders but were purchased for this project because of the importance of knowing exact flowrates for the experiments.

Column Operation

1. Modes of Operation

The distillation column was used in three different modes of operation (Figure A3). In Mode I, the ethanol was stripped from the fermented corn mash. This Mode used nine trays with no reflux, resulting in a product of 65 vol % ethanol and an ethanol-free bottoms product. Mode I operation had a feed or mash flowrate of 43.1 gallons per hour, and a distillate flowrate of 6.9 gallons per hour. The bottoms product was screened and used for feed and the distillate was either used for fuel in tractor experiments or was further purified in Mode II.

Mode II was operated with reflux and 10 trays and used the Mode I distillate (65 % ethanol) as feed. It produced a distillate of 85 vol % ethanol and a bottoms of 15 vol % ethanol. The bottoms were mixed with the corn mash feed for Mode I and the distillate was either used as fuel or further purified in Mode III.

Mode III was never required in our work since all of the Mode II distillate was used for fuel. Theoretically, Mode III (using reflux and 10 trays) should produce a 95 vol % ethanol distillate and an 80 vol % ethanol bottoms from the 85 vol % ethanol feed. It should be noted that distillation in the higher ethanol concentration ranges was far less efficient than in the lower ranges.

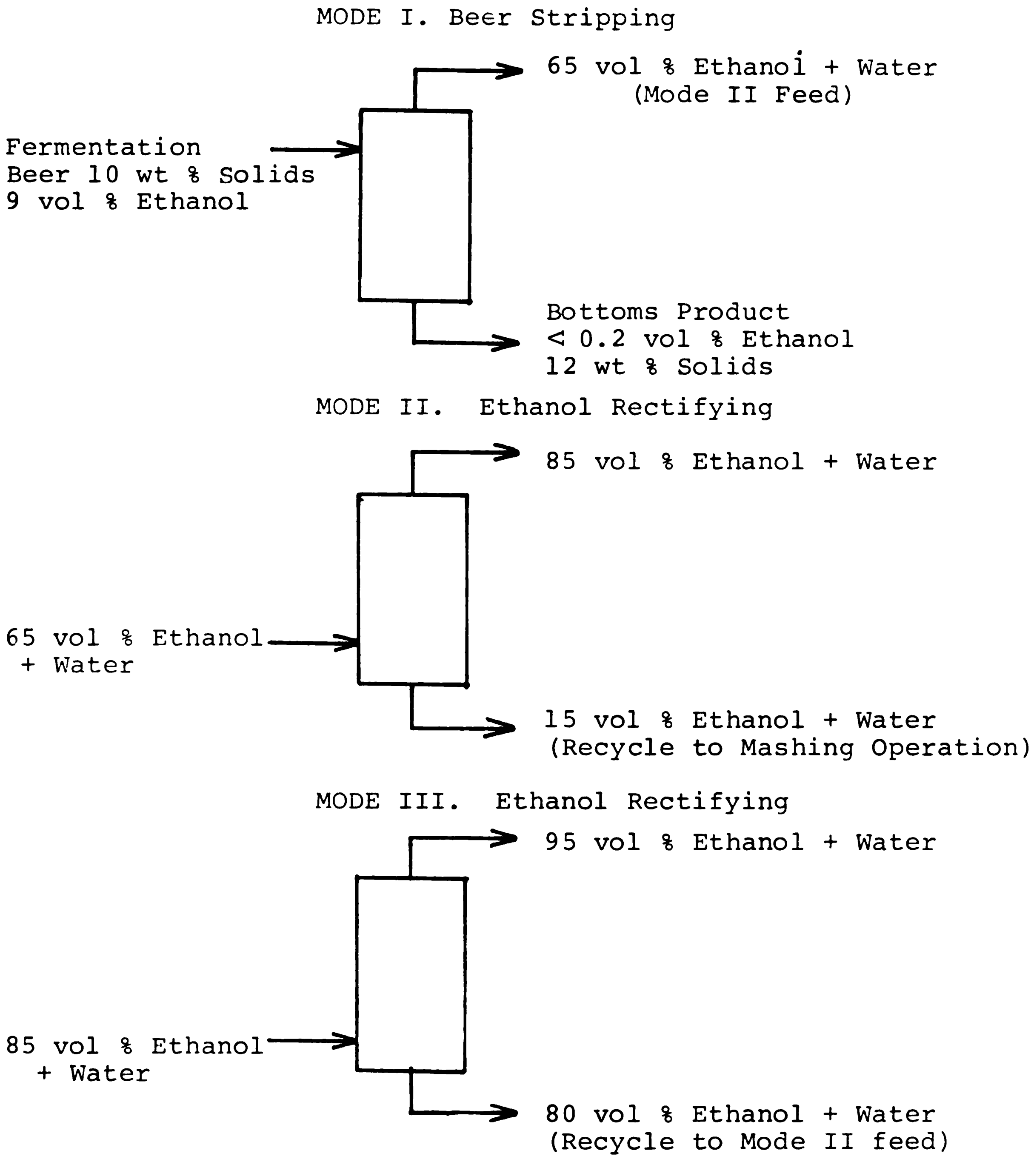


Figure A3. Modes of Operation for Small-Scale Distillation Column

2. Manual Column Operation

Fermentation mash was stripped of ethanol in a conventional stripping column to less than 0.2 vol % ethanol in the bottoms product. The subcooled feed entered the top tray and moved down the column. Vapor was generated using a steam coil immersed in a column bottoms. Overhead vapors were condensed and recovered. Bottoms were dewatered using a vibrating sceen system. Information for energy and material balances was obtained manually.

Operation of the distillation column revealed some unique features of corn mash distillation. The most important feature is the sensitivity of the overheads composition to vapor velocity through the tray holes. The column was initially configured with 42 holes of 11/32" diameter on each plate, resulting in overheads product of 22-26% ethanol. Since some weeping was observed under normal column operation conditions, 10% of the holes were plugged on each plate. The overheads product jumped to 66-70% ethanol with no change in the other operating conditions. Plugging another 10% of the holes caused a reduction in the overheads ethanol composition. The distillation of fermented mash seemed sensitive to the open area on the plates, which controlled the vapor flow rate across the trays. Liquid flow rates of feed and bottoms also required careful adjustment to obtain maximum separation in the stripping operation. Apparently there was a narrow operating range of vapor and liquid flow rates for optimal separation when fermentation beer was the feed. The feed and boilup rates should be controlled as suggested in the control discussion to ensure operation within this narrow range.

Operation of the column was completely manual, requiring an operator to watch over the process at all times. The distillation of a normal-sized 500 gallon batch required 10 hours of operation which usually produces 35 to 40 gallons of ethanol on an anhydrous basis.

The column was cleaned after every batch by flushing with water immediately after distillation. Plugging was a problem when the mash was allowed to dry, so washing the column after each batch was necessary. Plugging could be detected in a steel column by observing an increase in pressure drop through the column. This might be done by installing pressure taps on the column.

Material Balance

One of the goals of this project was to make material and energy balances on the small scale ethanol process. The material balances were vital for identifying causes of material and energy losses. Low yields of ethanol from the corn feed were caused by poor starch conversion or ethanol losses in the process. The material balance pinpointed these problems. Specific material balance data of four typical runs are tabulated in Tables A6 to A9. The starch conversion and overall yield values are listed in Table A10.

was 7% of the total ethanol produced. The amount of ethanol lost by evaporation during fermentation was found to be higher than the amount lost with the column bottoms (2%). In support of this high fermentation loss is the fact that most designs in the literature for larger ethanol plants recommend ethanol scrubbers for fermentation vapors.[6,7] This 7% loss of ethanol is significant and scrubbers should be considered for all size facilities even though many small-scale designs overlook the importance of scrubbers for fermenters.[5]

The difference between the gas chromatograph and the hydrometer measurements ranged from 1.7 to 4.6% in the four trials. This error is low enough to permit using hydrometers for small scale plants. The only problem is the measurement of low ethanol concentrations in the column bottoms if losses are expected. Hydrometers are not accurate at very low concentrations and other methods should be used. A bottoms temperature monitor or a bottoms temperature control are two alternatives which can be used to assure bottoms purity. The hydrometer used in the trials had a built-in thermometer for temperature correction and had an overall precision of 0.25 volume %. This range of error can be expected for all material and yild calculations when using a hydrometer of similar quality for ethanol concentration measurements.

Fermentation ethanol was produced from ground corn (see Figure A4) via the following steps: (1) cooking and saccharification; (2) fermentation; (3) distillation; (4) ethanol upgrading; (5) bottoms dewatering. All pertinent weights and compositions were measured and recorded for each batch (Table A5). Corn with 12 vol % moisture and 60 vol % starch was the process feed. The slurry in the fermenter was 17 vol % solids at the beginning of fermentation. About 5 vol % of the fermentor contents was lost during the fermentation to a starch endpoint. Most of this loss was carbon dioxide gas. Only 6 to 7 vol % starch was left in the stripped product. Sixty-five vol % ethanol was produced by stripping the beer under Mode I operation.

Ethanol compositions were measured by both a gas chromatograph and a hydrometer as a check on the accuracy of the hydrometer readings. Separate material balances were also done using the data from each method (Tables A6 to A9) to find any propagation of error caused by using hydrometer measurements.

Starch compositions of the initial corn and bottoms product were measured using the Macrae and Armstrong method.[9] This method used a specific hydrolysis of starch to glucose and measured the resultant glucose to determine the starch content.

All component weights were measured in the cooker-fermenter tank. The apparatus was constructed on a scale

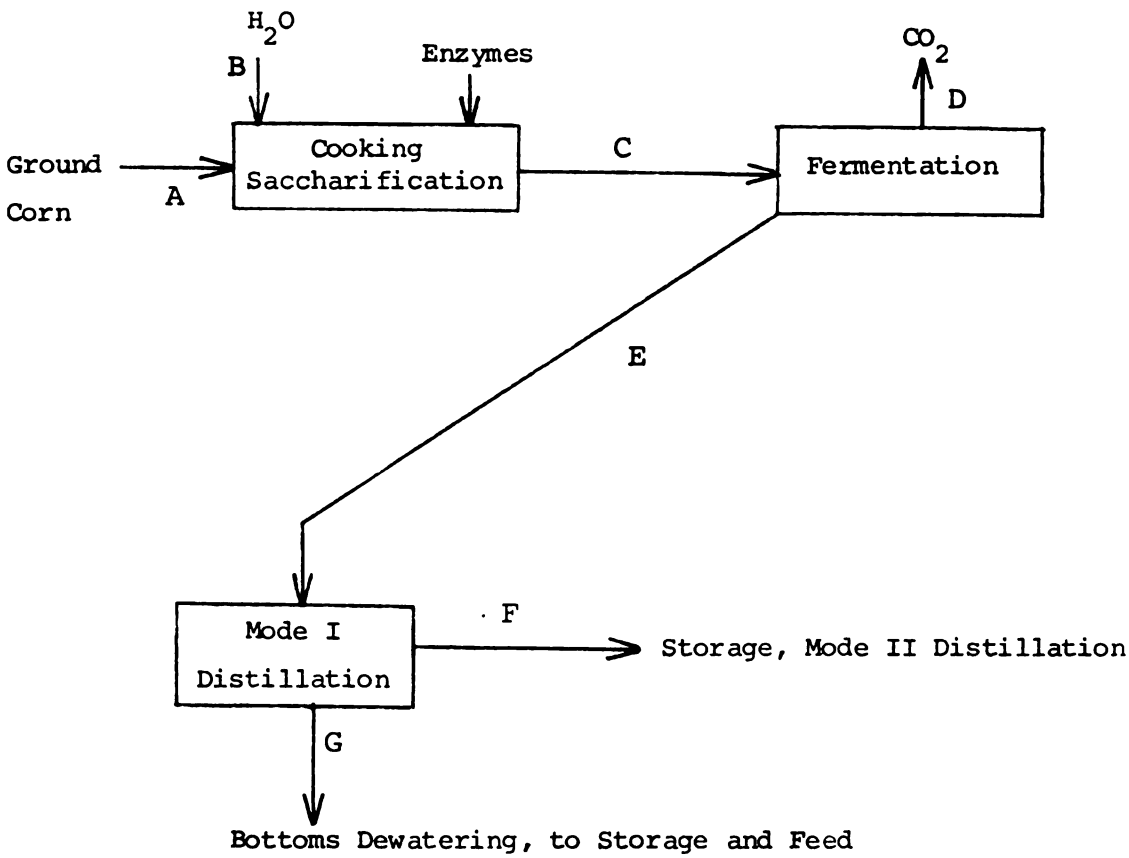


Figure A4. Small-Scale Ethanol Fermentation Process Diagram.

Table A5. Raw Data for Material Balance

	10/24 Batch	10/28 Batch	11/3 Batch	11/19 Batch
Lbs. Wet Corn	992.0	881.0	951.0	940.0
Fraction Dry Material	.882	.882	.879	.9032
Lbs. Water Plus Corn	4815.0	4145.0	4475.0	4428.0
Fraction (8) Starch	.596	.596	.598	.587
Lbs. Lost in Fermentation	254.0	332.0	300.0	300.0
Fraction Starch (8) in Bottoms Mash	.0653	.0700	.0628	.0628
Gallons Ethanol-Water Product	60.0	68.0	60.0	63.0
Vol % Ethanol[a] in Product	62.3	60.2	69.0	60.0
Vol % Ethanol[b] in Product	64.17	62.29	70.25	72.80
Vol % Ethanol[b] in Feed	8.63	10.40	10.27	7.52
Vol % Ethanol[b] in Bottoms	.30	.33	.60	.08

[a]Hydrometer Measurement

[b]Gas Chromatograph Measurement

Table A6. Overall Material Balance (lbs/batch)

A. Using Gas Chromatograph for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry)	874.9	---	874.9	---	358.2	---	358.2
Starch	(521.8)	---	(521.8)	---	(23.4)	---	(23.4)
Protein	(353.1)	---	(353.1)	---	(334.8)	---	(334.8)
Water	117.1	3823.0	3940.1	0.4[a]	3939.7	198.3	3741.4
Ethanol	---	---	---	2.3[a]	263.1	254.1	9.0
					(56.17 wt%)[b]		(.24 wt%)[b]
CO_2	---	---	---	251.3[a]	---	---	---
Total	992.0	3823.0	4815.0	254.0	4561.0	452.4	4108.6

Yield = 2.11 gal. abs. Ethanol/Bu Corn Starch Conv. = .955

[a]Theoretically calculated

[b]Gas Chromatograph Measurement

Table A6. (Continued)

B. Using Hydrometer for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry	874.9	---	874.9	---	375.4	---	375.4
Starch	(521.8)	---	(521.8)	---	(24.5)	---	(24.5)
Protein	(353.1)	---	(353.1)	---	(350.9)	---	(350.9)
Water	117.1	3823.0	3940.1	1.4[a]	3938.7	207.7	3731.0
Ethanol	---	---	---	8.6[a]	246.9 (54.3 wt%)[b]	246.9	---
CO_2	---	---	---	244.0[a]	---	---	---
Total	992.0	3823.0	4815.0	254.0	2561.0	454.6	4106.4

Yield = 2.05 gal. abs. Ethanol/Bu Corn   Starch Conv. = .953

[a] Theoretically calculated

[b] Hydrometer Measurement

Table A7. Overall Material Balance (lbs/batch)

A. Using Gas Chromatograph for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry)	777.0	---	777.0	---	156.6	---	156.7
Starch	(463.4)	---	(463.4)	---	(11.0)	---	(11.0)
Protein	(313.6)	---	(313.6)	---	(145.7)	---	(145.7)
Water	104.0	3264.0	3368.0	3.9[a]	3364.1	229.2	3134.2
Ethanol	---	---	---	25.1[a]	292.2	284.0	8.2
					(55.27 wt%)[b]		
CO_2	---	---	---	303.0[a]	---	---	
Total	881.0	3264.0	4145.0	332.0	3813.0	513.9	3299.1

Yield = 2.61 Starch Conv. - .980

[a]Theoretically calculated

[b]Gas Chromatograph Measurement

Table A7. (Continued)

B. Using Hydrometer for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry)	777.0	---	777.0	---	180.3	---	180.3
Starch	(463.4)	---	(463.4)	---	(12.6)	---	(12.6)
Protein	(313.6)	---	(313.6)	---	(167.7)	---	(167.7)
Water	104.0	3264.0	3368.0	5.4[a]	3362.6	247.8	3114.8
Ethanol	---	---	---	35.1[a]	270.1	270.1 (52.15 wt%)[b]	---
CO_2	---	---	---	291.5[a]	---	---	---
Total	881.0	3264.0	4145.0	332.0[a]	3813.0	517.9	3295.1

Yield = 2.52 Starch Conv. = .976

[a] Theoretically calculated

[b] Hydrometer Measurement

Table A8. Overall Material Balance (lbs/batch)

A. Using Gas Chromatograph for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry	835.9	---	835.9	---	242.9	---	242.9
Starch	(500.2)	---	(550.2)	---	(15.3)	---	(15.3)
Protein	(335.7)	---	(335.7)	---	(227.6)	---	(227.6)
Water	115.1	3524.0	3639.1	1.9[a]	3637.2	166.9	3470.3
Ethanol	---	---	---	8.2[a]	294.9	278.2	16.7
					(62.50 wt%)[b]		(.48 wt%)[b]
CO_2	---	---	---	289.9[a]	---	---	---
Total	951.0	3524.0	4475.0	300.0	4175.0	445.1	3729.9

Yield = 2.41 gal/abs. ethanol/bu corn

Starch Conv. = .969

[a] Theoretically calculated

[b] Gas Chromatograph Measurement

Table A8. (Continued)

B. Using Hydrometer for Concentration Measures

Stream	A	B	C	D	E	F	G
Corn (Dry)	835.9	---	835.9	---	265.2	---	265.2
Starch	(500.2)	---	(500.2)	---	(16.7)	---	(16.7)
Protein	(335.7)	---	(335.7)	---	(248.5)	---	(248.5)
Water	115.1	3524.0	3639.1	2.7[a]	3636.4	173.3	3463.1
Ethanol	---	---	---	17.1[a]	273.4	273.4 (61.2 wt%)[b]	---
CO_2	---	---	---	280.2[a]	---	---	---
Total	951.0	3524.0	4475.0	300.0	4175.0	446.7	3728.3

Yield = 2.37 gal abs. ethanol/bu corn Starch Conv. = .967

[a]Theoretically calculated

[b]Hydrometer Measurement

Table A9. Overall Material Balance (lbs/batch)

A. Using Gas Chromatograph for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry	849.0	---	849.0	---	289.5	---	289.5
Starch	(498.0)	---	(498.0)	---	(18.2)	---	(18.2)
Protein	(351.0)	---	(351.0)	---	(271.3)	---	(271.3)
Water	91.0	3488.0	3579.0	3.6[a]	3575.4	215.6	3359.8
Ethanol	---	---	---	23.1[a]	263.1	261.1	2.0
					(54.77 wt%)[b]	(.06 wt%)[b]	
CO_2	---	---	---	273.3[a]	---	---	---
Total	940.0	3488.0	4428.0	300.0	4128.0	476.7	3651.3

Yield = 2.32 gal. abs. ethanol/bu corn

Starch conv. = .964

[a]Theoretically calculated

[b]Gas Chromatograph Measurement

Table A9. (Continued)

B. Using Hydrometer for Concentration Measurements

Stream	A	B	C	D	E	F	G
Corn (Dry)	849.0	---	849.0	---	308.2	---	308.2
Starch	(498.0)	---	(498.0)	---	(19.4)	---	(19.4)
Protein	(351.0)	---	(351.0)	---	(288.8)	---	(288.8)
Water	91.0	3488.0	3579.0	8.6[a]	3570.4	230.6	3339.8
Ethanol	---	---	---	27.2[a]	249.4	249.4 (51.95 wt%)[b]	---
CO_2	---	---	---	264.2	---	---	---
Total	940.0	3488.0	4428.0	300.0	4128.0	480.0	3648.0

Yield = 2.13 gal abs. ethanol/bu corn   Starch Conv. = .961

[a]Theoretically calculated

[b]Hydrometer Measurement

so all measurements can be easily taken. The only drawback to this scale is its low precision of $\pm\frac{1}{2}$ lb.

The material balance summary for four typical runs is shown in Table A10.Overall yield values, though quite variable, were all below the maximum possible yield of 2.7 gallons absolute ethanol per bushel and can be improved upon with further work.[9] The large yield fluctuations in the trials (2.11-2.62 gal. anhydrous ethanol/Btu) were due primarily to cooking and fermentation problems. Cooking times, temperatures, and pH variations along with enzyme and yeast amounts were the major causes. This problem was also revealed by the variations in starch conversion. Further experimentation with these parameters and a more automated system could solve most of these problems.

Ethanol losses in the process occurred in fermentation and distillation. The fermentation losses were from evaporation during the 48 hours of fermentation. The distillation losses occured from low concentrations of ethanol in the bottoms liquid.

As shown by Table A11, fermentation ethanol losses appeared to be substantial, but these losses were calculated from the theoretical yield of CO_2 and the relative volatility of ethanol to water. The wide variation in the values can be attributed to the method of calculation. The best estimate for ethanol losses during fermentation was 7% of the total ethanol produced. The amount of ethanol lost by evaporation during fermentation was found to be higher than the amount lost with the column bottoms (2%). This high fermentation loss seemed reasonable since most designs in the literature for larger ethanol plants recommend ethanol scrubbers for fermentation vapors.[6, 7] This 7% loss of ethanol is significant and scrubbers should be considered for all size facilities even though many small-scale designs overlook the importance of scrubbers for fermenters.[5]

The difference between the gas chromatograph and the hydrometer measurements ranged from 1.7 to 4.6% in the four trials. This error was low enough to permit using hydrometers for small scale plants. The only problem was the measurement of low ethanol concentration in the column bottoms if losses are expected. Hydrometers were not accurate at very low concentrations and other methods should be used. A bottoms temperature monitor or a bottoms temperature control are two alternatives which can be used to assure bottoms purity. The hydrometer used in the trials had a built-in thermometer for temperature correction and had an overall precision of 0.25 volume %. This range of error can be expected for all material and yield calculations when using a hydrometer of similar quality for ethanol concentration measurements.

Table A10. Material Balance Summary

	10/24 Batch	10/28 Batch	11/3 Batch	11/19 Batch	Average
Yield[a] (Gal. Abs. Ethanol/ bu Corn)	2.11	2.62	2.41	2.23	2.34
Yield[b] (Gal. Abs. Ethanol/ bu Corn)	2.05	2.52	2.37	2.13	2.27
% Error in Hydrometer Measurements	2.9	3.5	1.7	4.6	3.2
Starch Conversion	.955	.980	.969	.964	.967

[a]Gas Chromatograph Measurement

[b]Hydrometer Measurement

Table All. Summary of Ethanol Losses

	10/24 Batch	10/28 Batch	11/3 Batch	11/19 Batch	Average
Total lbs. absolute Ethanol Produced	265.4	317.3	303.1	286.2	293.0
Lbs. Ethanol Lost[a] in Fermentation	2.3	25.1	8.2	23.1	14.7
Wt% Ethanol in Bottoms	.24	.26	.48	.06	.26
Total lbs. Ethanol Lost in Bottoms	9.0	8.2	16.7	2.0	9.0
% of Total Lost in Fermentation	.87	7.9	2.7	8.1	5.0
% of Total Lost in Distillation	3.4	2.6	5.5	.70	3.1
% of Total Lost in Overall Process	4.3	10.5	8.2	8.8	8.1

[a]Values include weight loss from secondary fermentations, aldehyde evaporation and all other weight losses except water.

Energy Balance

One of the unanswered questions about small-scale ethanol production is whether the energy balance around the process is positive. Distillation is one of the most energy-intensive steps in fermentation ethanol production. In this project an energy balance was made around the distillation column for the purpose of identifying energy losses and their magnitude.

The energy balance was performed by measuring the temperatures, flowrates and compositions of all streams to the column. The 100 psig steam used in the reboiler was assumed saturated and the condensate was weighed for the flowrate. The compositions of the streams were measured by a gas chromatograph and all stream flows (distillate (D), feed (F), steam (S), and bottoms (B), [see Figure A5]) were also collected and measured. This raw data, which is listed in Table All, was the basis for the energy balance calculation around the distillation column.

Energy losses in the distillation process and total energy input values were the most important results of the energy balance. The energy loss data located energy leaks in the system to be corrected (i.e., insulation) to improve the efficiency of the column. The total energy input per gallon of anhydrous ethanol produced gave an energy cost for distillation and suggested that further energy saving steps should be taken.

The results in Table A13 show an average energy loss from the column of 23% which is the amount of the total energy input lost to the surroundings. The distillation column was ½-inch thick glass. Glass is a farily good insulator; therefore, it was assumed that no insulation was required. An energy loss of 23% proves that further insulation is definitely required.

The measured total energy input per gallon of anhydrous ethanol is 32,076 Btu/gal anhydrous ethanol for Mode 1 operation producing a 65 vol % ethanol product. Mode II and Mode III operation to purify the ethanol would require a calculated total input energy of 56,578.4 Btu/gal. Anhydrous ethanol.* Producing a 95 vol % ethanol overheads product from one large column would require 42,971.0 Btu/gal anhydrous ethanol.** This value includes 23% loss of heat to the atmosphere and no energy recovery systems (heat exchangers) in the process. SRI [7] estimated that 39,560 Btu/gal. anhydrous ethanol was required to distill a 95 vol % overhead product in a 25 million gallon per year plant using no energy recovery. Based on the energy balance of this study, the SRI estimate seems to be realistic. The difference between the SRI estimate (39,560 Btu/gal.) and the estimate of this study (42,971 Btu/gal.) can be attributed to small-scale inefficiencies and lack of proper insulation.

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*Measured Value
**Calculated Values

An absolute minimum value of 21,220 Btu/gal anhydrous ethanol was calculated assuming an infinite number of trays, perfect heat transfer, and no energy recovery. This is an ideal or perfect value and is not physically possible to attain but serves as a basis to compare with other values to judge their validity. The large difference between this minimum value (21,220 Btu/gal) and the estimated values of SRI (39,560 Btu/gal) and of this study (42,971 Btu/gal) can be attributed to normal inefficiencies in equipment and error in techniques.

One gallon of anhydrous ethanol contains 84,800 Btu of usable energy as fuel. The distillation of 95 vol % ethanol from corn mash uses about 50% of this obtainable energy. These high values of energy consumption for distillation illustrates the need for energy recovery systems or heat exchangers to recover the heat from hot exiting streams. As an example of the possible energy savings, Katzen[6] estimated for a 50 million gallon per year plant with extensive energy recovery that 18,140 Btu/gal anhydrous ethanol would be required to distill at 100 vol % ethanol product. This is a 54% savings over the SRI value (39,560) in distillation energy usage which illustrates the importance of energy recovery systems. This distillation energy balance also underscores the importance of using nonpetroleum energy sources for producing ethanol on the small scale.

Experimental Conclusions and Recommendations

The feasibility of small scale fermentation ethanol production is highly dependent on the efficiency of the distillation process. The distillation column design basis for this project was directed at the goal of maximum efficiency as well as column operation. The resultant column provided much useful information to help meet these ends.

Having glass as the column wall proved to be extrememly useful in troubleshooting problems, such as tray plugging and other flow problems during operation. The glass column is also corrosion resistant, easy to disassemble for maintenance, and a better insulator than metal.

The reboiler to the process used steam heated coils. A heat exchanger system, such as steam coils, is highly recommended over injected steam because of the higher solids content of the bottoms product. By using a heat exchanger, the condensate latent heat can be recovered by recycling condensate back to the boiler to make more steam. This procedure conserves energy in the overall steam production process. Injected steam increases the liquid flow rates below the feed tray and thereby increases the vapor flow rate and reduces column efficiency.

The energy efficiency of the distillation process is measured by the energy loss to the surroundings and the total energy required per gallon of anhydrous ethanol produced. The measured values of 23% loss of input heat

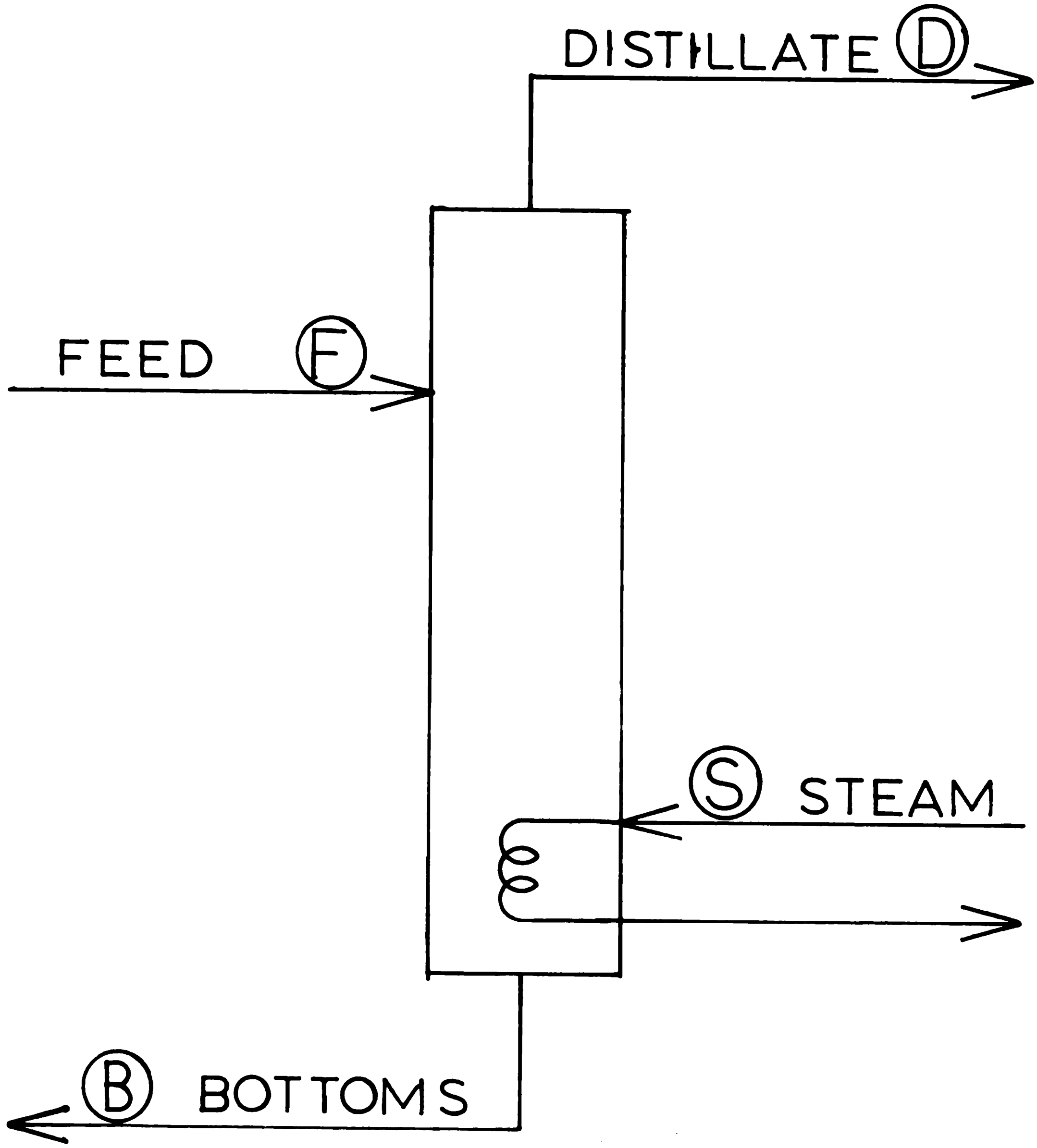
Table A12. Raw Data for Energy Balance

Time Interval Min	Steam S, lb/min	Steam S, Btu/min	Feed F lb/min	Wt Frac X_F	Feed F Btu/min	Dist. D lb/min	Wt. Frac. X_D	Dist. D Btu/min	Bottoms B lb/min
9	1.528	1541	8.417	.058	243	0.500	.526	324	7.917
10	1.875	1891	7.425	.058	214	0.800	.550	540	6.625
10	1.90	1916	7.1	.061	205	0.800	.548	532	6.300
10	1.875	1891	6.424	.058	186	0.774	.542	529	5.650
15	1.717	1732	5.7	.060	165	0.600	.472	339	5.60
16	2.105	2123	8.066	.048	235	0.882	.532	579	7.18
20	1.765	1780	7.118	.061	207	0.765	.627	557	6.353
22	2.205	2224	7.285	.051	230	.9318	.409	486	6.353
21	1.702	1716	7.298	.061	243	.0560	.426	292	6.738
20	2.100	2118	7.088	.051	236	.0963	.438	528	6.125

Table A13. Energy Balance Results

Time Interval Min.	Heat Input F&S Btu/min.	Heat Output D+B Btu/min.	Heat Loss H_{Loss} Btu/min.
9	1784	1763	21
10	2105	1744	361
10	2121	1677	444
10	2077	1541	536
15	1897	1357	540
16	2358	1816	542
20	1987	1652	335
22	2454	1581	873
21	1959	1453	506
20	2354	1584	770

Figure A5. Flow Diagram for Distillation
Column Energy Balance Calculations


DISTILLATE D
FEED F
S STEAM
B BOTTOMS

and 32,076 Btu/gal anhydrous ethanol to produce 65 vol % ethanol product should be typical of uninsulated small-scale distillation columns. These values also indicate that the distillation column is inefficient by comparison to literature sources and should be improved. Insulation around all hot surfaces and heat exchangers for recovery of heat from hot exiting streams should be used to maximize efficiency and save energy.

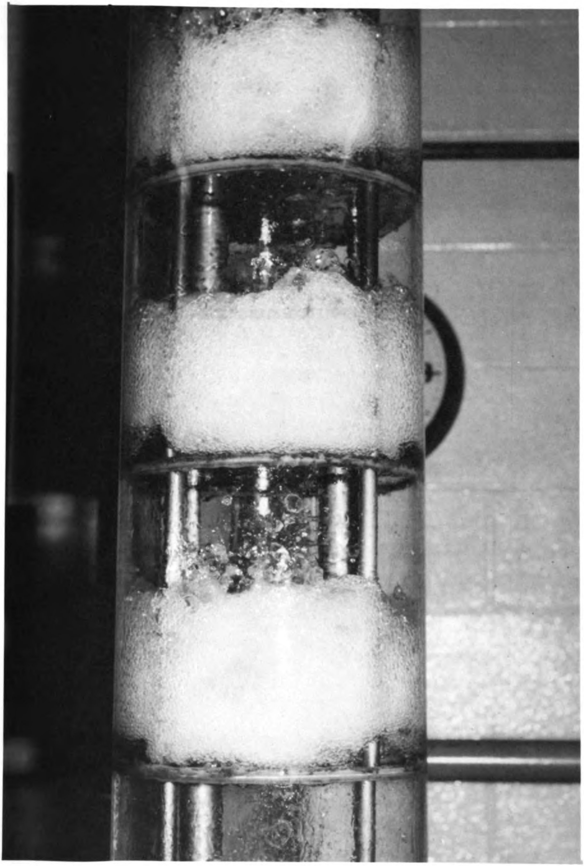
A distillation column has no effect on ethanol yields since an efficient column loses very little ethanol as shown in Table All. Yields are primarily dependent on starch conversion and fermentation processes. If gallons of ethanol per bushel yields are low, these are the steps that should be reviewed.

Column controls are important in obtaining consistent and optimal operation while reducing labor requirements of the distillation process. Temperature-controlled steam flow and reboiler level control are recommended to maximize ethanol stripping from the bottoms product. Feed control is also recommended to ensure consistent fuel flowrates which stabilize column operation. The cost of control components as shown in Table high but can be justified by the savings in labor costs and the efficient column operation.

Figure A6. Photograph of Distillation Apparatus of Experimental Small Scale Facility


NO SMOKING

Figure A7. Photograph of Sieve Trays in Rectification Mode of Operation



APPENDIX B:

SCENARIO EQUIPMENT LISTS

TABLE B1. Scenario I: EQUIPMENT LIST

Quantity	Description
1	6000 Gal. Batch Cooker (Mild Steel)
1	Cooker Transfer Cavity Pump (.75 Hp)
4	6000 Gal. Fermentation Tank (Mild Steel)
3	Circulation and Transfer Cavity Pump (.75 Hp)
1	55 Gallon Enzyme Prep. Tank (Stainless)
1	Enzyme Agitator (.5 Hp)
1	Enzyme Centrifugal Pump (.25 Hp)
1	Ferment Fan Cooler (525 ft.^{2}, 2 Hp)
1	Grain Conveyor (100 ft., 5 Hp)
1	Distillation Assembly Stripping Column - Sieve (9" x 20', Glass) Rectifying Column - Packed (9" x 30', Glass) Column Supports
1	Vapor Condenser (40 ft.^{2}, Stainless)
1	Feed Preheater (50 ft.^{2}, Stainless)
12	Control Valves
50	Manual Valves
1	Centrifugal Reflux Pump (.5 Hp)
2	Cavity Stillage - Feed Pumps (.75 Hp)
1	Stillage Surge Tank - 5000 Gal. (Mild Steel)
1	20,000 Gallon Alcohol Storage Tank (Fiberglass)
1	Dehydration Unit (Molecular Sieve) 2 Absorption Columns 1000 16 Sieves 2.7 Hp. Blower, 23 Hp. Heater
2	Cavity Byproduct Pump (.75 Hp.)
1500 ft.	Piping (1000 ft. PVC, 500 ft. Stainless)
1	Boiler Facility (14 psi) Coal Fired Boiler (75 lb/hr) Boiler Feed Pump (.5 Hp) Water Filter and Softener
1	Well Water Pump (1 Hp)
1	Vibrating Screen and Press (1 Hp)
1	Stillage - Filler Mixer (5 Hp)
2	Filtrate Centrifugal Pumps (.75 Hp)

TABLE B1. (continued)

Quantity	Description
1	55 Gallon Water Surge Tank (Mild Steel)
1	Roller Mill (5 Hp)
1	5000 Bu Grain Storage Bin (Mild Steel)
1	Grain Dryer
1	Storage Building (30' x 60')

TABLE B2. Scenario II: EQUIPMENT LIST

A) Farm Facility

Quantity	Description
1	6000 Ga. Batch Cooker (Mild Steel)
1	Cooker Transfer Cavity Pump (.75 Hp)
4	6000 Gal. Fermentation Tank (Mild Steel)
3	Circulation and Transfer Cavity Pumps (.75 Hp)
1	55 Gal. Enzyme Prep. Tank (Stainless)
1	Enzyme Agitator (.5 Hp)
1	Ferment Fan Cooler (525 ft.^{2}, 2 Hp)
1	Distillation Assembly Stripping Column - Sieve (9" x 20', Glass) Rectifying Column - Packed (9" x 30', Glass)
1	Vapor Condenser (40 ft.^{2}, Stainless)
1	Feed Preheater (50 ft.^{2}, Stainless)
1	Centrifugal Reflux Pump (.5 Hp)
2	Cavity Stillage - Feed Pumps (.75 Hp)
10	Control Valves
45	Manual Valves
1	5000 Gal. Stillage Surge Tank (Mild Steel)
1	20,000 Gal. Alcohol Storage Tank (Fiberglass)
2	Cavity Byproduct Pumps (.75 Hp)
1400 ft.	Piping (1000 ft. PVC, 400 ft. Stainless)
1	Boiler Facility (14 psi) Coal Fired Boiler (75 lb/hr) Boiler Feed Pump (.5 Hp) Water Filter and Softener
1	Well Water Pump (1 Hp)
1	Vibrating Screen and Press (1 Hp)
1	Stillage - Filler Mixer (5 Hp)
2	Filtrate Centrifugal Pumps (.75 Hp)
1	55 Gallon Water Surge Tank (Mild Steel)
1	Roller Mill (5 Hp)
1	5000 Bu Grain Storage Bin (Mild Steel)
1	Grain Dryer
1	Storage Building (30' x 60')

TABLE B2. (continued)

B) Water Extraction Plant

Quantity	Description
2	Tanker Trucks (20,000 Gallon, 4 mi/gallon)
2	50,000 Gallon Storage Tanks (Mild Steel)
2	Centrifugal Transfer Pumps (2.0 Hp)
3	Centrifugal Reflux Pumps (.75 Hp)
2	Centrifugal Feed Pumps (.75 Hp)
2	Centrifugal Bottoms Pumps (.75 Hp)
1	Alcohol Removal Column (15" x 40', Stainless)
1	Benzene Removal Column (10" x 30', Stainless)
1	Water Removal Column (8" x 30', Stainless)
1	Settler (200 gal., Mild Steel)
1	Condenser (500 $ft.^2$, Stainless)
1	5,000 Gal. Benzene Storage Tank (Mild Steel)
600 ft.	PVC Piping (Sched. 80)
600 ft.	Stainless Piping (Sched. 40)
15	Control Valves
50	Manual Valves
1	Steam Boiler Unit Coal Fired Boiler (20 lb/hr)
1	Office and Storage Building (60' x 80')

TABLE B3. Scenario III: EQUIPMENT LIST

A) Farm Facility

Quantity	Description
1	6000 Gal. Batch Cooker (Mild Steel)
1	Cooker Transfer Cavity Pump (.75 Hp)
4	6000 Gal. Fermentation Tank (Mild Steel)
3	Circulation and Transfer Cavity Pumps (.75 Hp)
1	55 Gal. Enzyme Prep. Tank (Stainless)
1	Enzyme Agitator (.5 Hp)
1	Ferment Fan Cooler (525 $ft.^2$, 2 Hp)
1	Distillation Assembly Stripping Column - Sieve (9" x 20', Glass) Column Supports
1	Vapor Condenser (40 $ft.^2$, Stainless)
1	Feed Preheater (50 $ft.^2$, Stainless)
2	Cavity Stillage - Feed Pumps (.75 Hp)
8	Control Valves
45	Manual Valves
1	5000 Gal. Stillage Surge Tank (Mild Steel)
1	20,000 Gal. Alcohol Storage Tank (Fiberglass)
2	Cavity Byproduct Pumps (.75 Hp)
1200 ft.	Piping (800 ft. PVC, 400 ft. Stainless)
1	Boiler Facility (14 psi) Coal Fired Boiler (18.7 Hp, 75 lb/hr) Boiler Feed Pump (.5 Hp) Water Filter and Softener
1	Well Water Pump (1 Hp)
1	Vibrating Screen and Press (1 Hp)
1	Stillage - Filler Mixer (5 Hp)
2	Filtrate Centrifugal Pumps (.75 Hp)
1	55 Gal. Water Surge Tank (Mild Steel)
1	Roller Mill (5 Hp)
1	Grain Dryer
1	5000 Bu. Grain Storage Bin (Mild Steel)
1	Storage Building (30' x 60')

TABLE B3: (continued)

B) Refinery and Water Extraction Plant

Quantity	Description
2	Tanker Trucks (20,000 Gallon, 4 mi/gal.)
2	50,000 Gallon Storage Tanks
2	Centrifugal Tansfer Pumps (2.0 Hp)
4	Centrifugal Reflux Pumps (.75 Hp)
3	Centrifugal Feed Pumps (.75 Hp)
3	Centrifugal Bottoms Pumps (.75 Hp)
1	Alcohol Rectification Column (15" x 30', Stainless)
1	Alcohol Removal Column (15" x 40', Stainless)
1	Benzene Removal Column (10" x 30', Stainless)
1	Water Removal Column (8" x 30', Stainless)
1	Settler (2000 gal., Mild Steel)
1	5000 Gal. Benzene Storage Tank (Mild Steel)
700 ft.	PVC Piping (Sched. 80)
800 ft.	Stainless Piping (Sched. 40)
20	Control Valves
50	Manual Valves
1	Steam Boiler Unit (500 psi) Coal Fired Boiler (25 lb/hr)
1	Office and Storage Building (60' x 80')

APPENDIX C:

SCENARIO EQUIPMENT AND

OPERATING COSTS

TABLE C1. Scenario I: EQUIPMENT COSTS

Description	Capital Costs	Annual Payment 10-Yr. @ 15%
Batch Cooker	$30,000.00	$5977.55
Fermenter Tanks (4)	40,000.00	7970.08
Prog. Cavity Pumps (8)	20,000.00	3985.03
Enzyme Tank & Agitator	1,000.00	199.25
Fermentation Cooler	4,000.00	797.00
Distillation Aparatus	75,000.00	14,943.88
Vapor Condenser	5,000.00	996.26
Feed Preheater	3,000.00	597.76
Reflux Pump	1,500.00	298.88
Stillage Surge Tank and Agitator	8,000.00	1,594.01
Alcohol Storage Tank	10,000.00	1,992.52
Dehydration Unit	32,500.00	6,475.69
Piping - 1000 ft. PVC	1,000.00	199.25
Piping - 500 ft. Stainless	3,000.00	597.76
Boiler Unit	25,000.00	4,981.29
Stillage - Filler Mixer[a]	18,800.00	3,745.93
Control Valves	6,500.00	1,295.14
Manual Valves	3,500.00	697.38
Building	30,000.00	5,977.55
Surge Tank	100.00	19.93
Roller Mill	1,550.00	308.84
Grain Storage Bin	3,000.00	597.76
Grain Dryer	8,300.00	1,653.79
TOTAL	$330,750.00	$65,902.49

[a]To centrifuge, add $39,200 and water treatment.
To screen, subtract $8,000 and add water treatment.

TABLE C2. Scenario II: EQUIPMENT COSTS

A) Farm Facility

Description	Capital Costs	Annual Payment 10-Yr. @ 15%
Batch Cooker	$30,000.00	$ 5977.55
Fermenter Tanks (4)	40,000.00	7970.08
Cavity Pumps (8)	20,000.00	3985.03
Enzyme Tank and Agitator	1,000.00	199.25
Fermentation Cooler	4,000.00	797.00
Distillation Apparatus	75,000.00	14,943.88
Vapor Condenser	5,000.00	996.26
Feed Preheater	3,000.00	597.76
Reflux	1,500.00	298.88
Stillage Surge Tank and Agitator	8,000.00	1,594.01
Alcohol Storage Tank	10,000.00	1,992.52
800 ft. PVC Piping	800.00	159.40
400 ft. Stainless Piping	2,400.00	478.20
Boiler Unit	25,000.00	4,981.28
Stillage-Filler Mixer [a]	18,800.00	3,745.93
Control Valves	5,400.00	1,058.00
Manual Valves	3,500.00	697.38
Building	30,000.00	5,977.55
Surge Tank	100.00	19.93
Roller Mill	1,550.00	308.84
Grain Storage Bin	3,000.00	597.76
Grain Dryer	8,300.00	1,653.79
TOTAL	$296,350.00	$59,048.23

[a]To centrifuge, add $39,200 and water treatment.
To screen, subtract $8,000 and add water treatment.

TABLE C2. (continued)

B) Water Extraction Plant

Description	Capital Costs	Annual Payment 10-Yr. @ 15%
Tanker Trucks (2)	$150,000.00	$29,887.75
Storage Tanks (2)	37,000.00	7,372.31
2-Hp Centrifugal Pumps (2)	4,000.00	797.01
.75-Hp Centrifugal Pumps (7)	10,500.00	2,092.14
Alcohol Removal Column	45,000.00	8,966.33
Benzene Removal Column	40,000.00	7,970.07
Water Removal Column	38,000.00	7,571.56
Settler	3,000.00	597.76
Condenser	23,000.00	4,587.79
Benzene Storage Tank	2,000.00	398.50
Piping	4,200.00	836.86
Control Valves	7,500.00	1,494.39
Manual Valves	3,500.00	697.38
Steam Boiler	20,000.00	3,985.03
Building	100,000.00	19,925.17
TOTAL	$487,700.00	$97,175.04

TABLE C3. Scenario III: EQUIPMENT COSTS

A) Farm Facility

Description	Capital Costs	Annual Payment 10-Yr @ 15%
Batch Cooker	$30,000.00	$5,977.55
Fermenter Tanks (4)	40,000.00	7,970.08
Cavity Pumps (8)	20,000.00	3,985.03
Enzyme Tank and Agitater	1,000.00	199.25
Fermentation Cooler	4,000.00	797.00
Distillation Apparatus	45,000.00	8,966.33
Vapor Condensor	5,000.00	966.26
Feed Preheater	3,000.00	597.76
Stillage Surge Tank and Agitater	8,000.00	1,594.01
Alcohol Storage Tank	10,000.00	1,992.52
800 ft. PVC Pipe	800.00	159.40
400 ft. Stainless Pipe	2,400.00	478.20
Boiler Unit	25,000.00	4,981.28
Stillage-Filler Mixer [a]	18,800.00	3,745.93
Control Valves	4,300.00	856.78
Manual Valves	3,500.00	697.38
Building	30,000.00	5,977.55
Surge Tank	100.00	19.93
Roller Mill	1,550.00	308.84
Grain Storage Bin	3,000.00	597.76
Grain Dryer	8,300.00	1,653.79
TOTAL	$263,750.00	$52,552.63

[a] To centrifuge, add $39,200 and water treatment.
To screen, subtract $8,000 and add water treatment.

TABLE C3. (continued)

B) Refinery and Water Extraction Plant

Description	Capital Costs	Annual Payment 10-Yr. @ 15%
Tanker Trucks (2)	$150,000.00	$ 29,887.75
Storage Tanks (2)	37,000.00	7,372.31
2-Hp Centrifugal Pumps (2)	4,000.00	797.01
.75-Hp Centrifugal Pumps (10)	15,000.00	2,988.78
Alcohol Rectification Column	20,000.00	7,970.07
Alcohol Removal Column	45,000.00	8,966.33
Benzene Removal Column	40,000.00	7,970.07
Water Removal Column	38,000.00	7,571.56
Settler	3,000.00	597.76
Ethanol Condenser	5,000.00	996.26
Benzene Condenser	23,000.00	4,587.79
Piping	5,500.00	1,095.88
Control Valves	10,200.00	2,032.37
Manual Valves	3,500.00	697.38
Steam Boiler	52,000.00	10,361.09
Building	100,000.00	19,925.17
TOTAL	$571,200.00	$113,812.55

TABLE C4. Scenario I: OPERATING COSTS

Item	Cost Per Unit	Units Per Year	Annual Cost
Corn	$ 2.70/Bu	42,735 Bu	$115,385
Alpha Amylase	2.62/Liter	1,700 Liters	4,458
Glucoamylase	1.30/lb.	1,355 lbs.	1,761
Sulfuric Acid	1.17/gal.	810 gal.	945
Yeast	.90/lb.	1,140 lb.	1,026
Electricity	.032/kwh	1,105,500 kwh	35,400
Coal	40.00/ton	673 tons	26,900
Water [a]	1.25/1000 gal.	1,103,000 Gal.	1,380
Water Treatment [b]	-----	------	2,900
Labor	$15,000.00/operator	3 operators	45,000
Molec. Sieve	1.00/lb.	3,000 lbs.	3,000
Nitrogen [c]	16.00/100 lbs.	17,750 lbs.	2,800
Lab Tests	10.00/Test	875 tests	8,750
Insurance	------	-----	6,000
Maintenance	------	-----	5,000
Taxes	------	-----	2,500
		Annual Operating Cost:	$263,205

[a] Well water.

[b] Charge for upgrading well water for boiler feed.

[c] 100 lb. cylinders.

TABLE C5. Scenario II: OPERATING COSTS

A) Farm Facility

Item	Cost Per Unit	Units Per Year	Annual Cost
Corn	$ 2.70/Bu	42,735 Bu	$115,385
Alpha Amylase	2.62/Liter	1,700 Liters	4,458
Glucoamylase	1.30/lb.	1,355 lb.	1,761
Sulfuric Acid	1.17/Gal.	810 gal.	945
Yeast	.90/lb.	1,140 lbs.	1,026
Electricity	.032/kwh	603,580 kwh	19,315
Coal	40.00/ton	648 tons	25,920
Water [a]	1.25/1000 gal.	1,081,600 gal.	1,352
Water Treatment [b]	-----	-----	2,900
Labor	15,000.00/operator	3 operators	45,000
Insurance	-----	-----	6,000
Maintenance	-----	-----	5,000
Taxes	-----	-----	2,500
		Annual Operating Cost:	$231,562

[a] Well water.

[b] Charge for upgrading well water for boiler feed.

TABLE C5. (continued)

B) Water Extraction Plant

Item	Cost Per Unit	Units Per Year	Annual Cost
Diesel Fuel[a]	$ 1.30/gal.	3,000 gal.	$ 3,900
Benzene	1.85/gal.	750 gal.	1,390
Electric	.032/kwh	359,511 kwh	11,504
Coal	40.00/ton	135 tons	5,400
Water[b]	1.25/1000 gal.	3,299,714 gal.	4,125
Water Treatment[c]	-----	-----	8,668
Lab Tests	10.00/test	1,900 tests	19,000
Labor	15,000.00/operator	8 operators	120,000
Insurance	-----	-----	15,000
Maintenance	-----	-----	10,000
Taxes	-----	-----	4,500
		Annual Operating Cost:	$203,487

[a]Transport.

[b]Well Water.

[c]Charge for upgrading well water for boiler feed.

TABLE C6. Scenario III: OPERATING COSTS

A) Farm Facility

Item	Cost Per Unit	Units Per Year	Annual Cost
Corn	$ 2.70/Bu	42,735 Bu.	$115,385
Alfa Amylase	2.62/Liter	1,700 Liters	4,458
Glucoamylase	1.30/lb.	1,355 lb.	1,761
Sulfuric Acid	1.17/gal.	810 gal.	945
Yeast	.90/lb.	1,140 lb.	1,026
Electricity	.032/kwh	603,580 kwh	19,315
Coal	40.00/ton	522 tons	20,872
Water [a]	1.25/1000 gal.	870,953 gal.	1,090
Water Treatment [b]	-----	-----	2,338
Labor	15,000.00/operator	3 operators	45,000
Insurance	-----	-----	6,000
Maintenance	-----	-----	5,000
Taxes	-----	-----	2,500
		Annual Operating Cost:	$225,690

[a] Well water.

[b] Charge for upgrading well water for boiler feed.

TABLE C6. (continued)

B) Distillation and Water Extraction Plant

Item	Cost Per Unit	Unit Per Year	Annual Cost
Diesel Fuel[a]	$ 1.30/Gal.	4,210 Gal.	$ 5,473
Benzene	1.85/Gal.	750 Gal.	1,390
Electric	.032/kwh	632,880 kwh	20,252
Coal	40.00/ton	310 tons	12,400
Water[b]	1.25/1000 Gal.	5,283,139 gal.	6,604
Water Treatment[c]	-----	-----	13,877
Lab Tests	10.00/test	2,000 tests	20,000
Labor	15,000.00/operator	8 operators	120,000
Insurance	-----	-----	17,000
Maintenance	-----	-----	12,000
Taxes	-----	-----	4,500
		Annual Operating Cost:	$233,496

[a]Transport.

[b]Well Water.

[c]Charge for upgrading well water for boiler feed.

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