DOE/CS-80010-T2

FARM FUEL ALCOHOL PROJECT

PRELIMINARY REPORT ON FACILITY DESIGN

September 1979

Prepared by:

Robert S. Pile

Phillip C. Badger

Joseph C. Roetheli

Edward L. Waddell, Jr.

The report describes the design considerations for a farm-scale fuel alcohol production facility. The work was done under DOE contract No. DE-AI01-80CS80010 with the Tennessee Valley Authority.

CONTENTS

	Page
Symbols Used	iv
Introduction	1
Objective	2
Considerations in Sizing Production System	2
Facility Design	3
Safety Considerations	41
References	43
Ethanol and Water Volume, Molar, and Weight Relationship	45
Glossary	46

SYMBOLS USED

A	-	Area, ft^2 or in^2
B	-	Distillation column bottoms stream
c	-	Specific heat, Btu/lb·°F
d	-	Agitator diameter
D	-	Distillation product stream
D_t	-	Tank diameter
E-i	-	Heat exchanger "i"
ETOH	-	Ethanol, or ethyl alcohol
F	-	Distillation column feed stream
F_p	-	Packing factor
G	-	Vapor flow rate through column, lb/ft^2·sec
G'	-	Vapor flow rate through column, lb/hr
h_f or h_g	-	Enthalpy, Btu/lb
h_i or h_c	-	Heat transfer coefficient, Btu/hr·ft^2·°F
H, or Δh	-	Change in enthalpy, Btu/lb
H_2O	-	Water
K, or k	-	Thermal conductivity, Btu/ft^2·hr·°F/ft
L	-	Liquid flow rate through column, lb/ft^2·sec
L'	-	Liquid flow rate through column, lb/hr or lb/sec
L_R	-	Reflux flow
λ	-	Heat of vaporization
M	-	Mass, lbs
$MF_{i,j}$	-	Mole fraction of "i" in stream "j"
MW	-	Molecular weight
η	-	Angular speed, revolutions per unit of time

SYMBOLS USED

(Continued)

$N_{i,j}$	-	Number of moles of "i" in stream "j"
P-i	-	Pump "i"
ρ	-	Density
q	-	Heat requirement, Btu
Q	-	Heat transfer rate, Btu/hr
t	-	Time interval
T	-	Temperature, °F
u	-	Overall heat transfer coefficient, $Btu/ft^2 \cdot hr \cdot °F$
μ	-	Viscosity (absolute or kinematic)
v	-	Velocity, ft/sec
V'	-	Vapor rate leaving column, lb/hr

FARM FUEL ALCOHOL PROJECT

PRELIMINARY REPORT ON FACILITY DESIGN

INTRODUCTION

Using agricultural crops to produce alcohol for motor fuel has received much attention in recent years. Farm-produced alcohol can offer a dependable source of fuel for many agricultural production operations, especially if it is integrated into traditional farm enterprises. Such an integrated system could include the use of crops as alcohol feedstocks, wet stillage byproducts from grains as animal feeds, residues or wastes for cooking and distillation energy, and the sharing of equipment and labor with other farm enterprises.

Opinoins on producing ethanol from agricultural crops ranges from extremely negative to extremely positive for such aspects as distillation designs, energy balances, feed value of stillage, impact on food prices, crop yields, yields of alcohol from various crops, value as a fuel, life of equipment, and economics of production. However, facts regarding these aspects of farm-scale ethanol production are limited. The TVA-DOE Farm Fuel Alcohol Project is an attempt to develop an efficient farm-scale ethanol production system to gain more information on: (1) energy requirements for processes involved, (2) ethanol yields from grain and nongrain feedstocks, (3) equipment requirements and costs, (4) byproduct use, and (5) how ethanol production integrates into farm management systems.

OBJECTIVE

This report describes the design of a farm-based ethanol production system to be built by TVA at Muscle Shoals, Alabama. This facility will include cooking, fermentation, and distillation equipment to allow production of 8,000 to 12,000 gallons of fuel ethanol during a three to four month period each year. Output will be about 10 gallons of 190-proof ethanol per hour. Present components are sized to allow 12-14 hour daily operation as a semi-continuous batch system. Intent of the project is to document equipment and energy requirements, ethanol yields, and feasibility of small farm-based ethanol plants for farm fuel self-sufficiency.

Cooking and fermentation will be batch-type operations, and packed distillation columns will be used for separating ethanol from the fermented beer. Energy recovery and waste heat use are integrated when feasible. The fermented beer will be fed directly to the distillation columns without separation of solids. Although this is an area of concern, an economical method of separation could not be identified.

CONSIDERATIONS IN SIZING PRODUCTION SYSTEM

An equivalent of 8,000 to 12,000 gallons of fuel alcohol (of 190 proof) annually would be required to replace all gasoline and about 35 percent of diesel fuel used on a typical commercial row-crop farm in the Tennessee Valley. Based on these estimates, farm labor availability, and on discussions with farmers and agricultural workers, a production goal of 10,000 gallons of fuel during a three-to-four month period annually was selected for a farm fuel ethanol facility.

The following factors were considered in developing this design:

(1) Small size of the facility did not allow use of highly automated control systems.

(2) Most farmers have equipment, skills, and surplus materials to enable a large amount of owner-construction of the facility.

(3) A renewable fuel, or possibly coal, should be used for cooking and distillation energy. Most farmers prefer a wood or wood-waste fired system to a coal-fired unit, primarily because of cost and environmental problems associated with coal.

(4) Limited information is available on the value and handling requirements of wet stillage as a livestock feed, and farmers are convinced that this is necessary if corn or other grains are used as a feedstock. The Tennessee Valley region uses more grain than is produced, and imports grain from the Midwest.

(5) Several nongrain crops offer potential for ethanol production, and can be produced on more erosive soils with less fertilizer inputs and higher sugar or starch yields than corn. However, corn has received more emphasis as an ethanol feedstock and will be used initially in this test facility to establish benchmark data.

(6) Farm produced ethanol offers more potential for use as a direct fuel than for dehydration and use in an alcohol-gasoline blend, primarily due to the cost of dehydrating ethanol above the azeotrope.

FACILITY DESIGN

Design Criteria

The following design criteria were developed for the facility. Other specifications and assumptions are given in the component discussions.

Feedstock: Starches or sugars that can be fermented to an ethanol content of 8 volume percent.

Product Quality: Ethanol at 190 proof or 95 volume percent ethanol.

Production Rate: Nine to ten gallons of product per hour.

Recovery: Stillage to contain no more than 5 percent of the ethanol produced during fermentation.

Feedstock Handling

Initial fuel alcohol production feedstocks for this facility will be primarily grains with a later shift to nongrain feedstocks. On-site storage facilities, transfer equipment, measuring devices, and feedstock preparation equipment are essential. A high degree of accuracy should be attained in preparing feedstocks for liquefication, saccharification, and fermentation. Conventional grain handling equipment will satisfy this need in most cases. As alternative feedstocks are developed and processes identified, equipment needs will change.

Feedstock storage facility needs will vary according to preservation and storage characteristics of alternate feedstocks. Processing and handling equipment necessary to prepare the materials for alcohol production include:

(1) Storage facilities sized to allow for a predetermined period of operation. Factors affecting this will include feedstock type and availability, market fluctuations, capital investment required for the facilities, and total alcohol production desired.

(2) Materials handling equipment to transfer feedstock from storage to the processing equipment and then to the initial equipment involved in alcohol production. Associated with the transfer equipment should be a weighing or measuring device to determine the amount of material prepared.

(3) Processing equipment to prepare feedstock for liquification and saccharification. Conventional hammer mills, roller mills, or presses are required to prepare grains and sugar crops such as sorghums for the starch-sugar-alcohol conversion. Cooking vessels are also required for preparing starch base feedstocks.

Assumptions and equipment needs for feedstock handling for corn are listed below:

(1) Capability should be provided to store enough grain to operate the plant for one week.

(2) The corn must be milled to a minus 20-mesh final product size. Corn used in this facility will be obtained from a local feed company.

(3) An automatic weighing mechanism will be installed so that a known amount of corn can be transferred to the cook vessel.

(4) Conventional equipment will be adapted to handle feedstocks.

Based on the above requirements, equipment selected for this facility were:

(1) Bulk storage grain tank, 7.5 tons capacity.

(2) One 4-inch by 16-foot auger to transfer corn from storage to a weigher, and one 4-inch by 20-foot auger to transfer corn from weigher to cook vessel. Each auger will be driven by a 3/4-hp electric motor. (It may be possible to eliminate an auger by having the weigher dump directly into the cooker.)

(3) A weigher equipped with receiving and discharge hoppers. The weigher can be calibrated to drop a known amount of corn on each discharge.

(4) Electrical controls located such that the operator has control of both augers from one station.

All equipment used is available from most grain handling equipment suppliers.

Cooking

The feedstock handling equipment delivers the processed material to the cook vessel where the starch portion of the grain is converted to simple sugars by adding enzymes, water, and heat. Temperature and pH must be controlled during this process. Failure to maintain the appropriate conditions will hamper enzymatic conversion and reduce sugar available for alcohol fermentation.

The following activities are involved in preparing corn mash for fermentation: (1) mixing, (2) heating, (3) addition of enzymes, (4) gelatinization, (5) liquefication, and (6) cooling. Each activity affects the design of a cook vessel.

A recipe for preparing mash should detail the volume of mash to be prepared, time intervals associated with heating and cooling during the cycle, tolerable pH ranges (and corrective action) and amount and timing of each ingredient to be added: water, corn, and enzymes. The following recipe and procedure was based on recommendations of an enzyme and yeast supplier, and will be the procedure initially used in the evaluation facility.

(1) For start-up, 20 gallons of water per bushel of ground corn will be added to the cook vessel. Water quantity will be measured with a residential type water meter.

(2) Water will be heated and agitation will then be started and continued until the cooking cycle is completed.

(3) The appropriate amount of corn meal will be added via the weighing mechanism.

(4) The pH will be checked and adjusted to 5.5-6.0 if necessary by adding sulfuric acid or sodium hydroxide.

(5) An alpha-amylase enzyme will be added at a rate of 2 oz per 5 bushels of corn.

(6) The contents will be heated slowly to 172°F, and held for 30 minutes.

(7) The mixture will be heated to 212°F, and held for 15 minutes.

(8) The mixture will be cooled to 172°F by adding cold water. The pH should be 6.0-6.5, and will be adjusted if necessary.

(9) An alpha-amylase enzyme will be added to the mixture at a rate of 4 oz per 5 bushels of corn and the temperature held at 172°F for 30 minutes.

(10) The mixture will be cooled to 80°F by using cooling coils, and the pH adjusted to 4.0-4.5.

(11) An alpha-amyloglucosidase enzyme will be added to the mixture at the rate of 2 oz per 5 bushels.

(12) A prepared yeast culture slurry will be added. Slurry preparation rate is 4 oz of dried yeast per 5 bushels of corn.

(13) The mash will be transferred to the fermentation tank.

The preceding recipe can best be described by figure 1. The recipe may vary somewhat depending on the yeast and enzymes used.

During evaluations, the volumes of water added will be reduced to increase alcohol content in the beer to approximately eight percent. Experiments will also be used to define permissible tolerances on process conditions and measurements of ingredients. This recipe was used to determine quantities of each material, heat energy required, and cooling water required to prepare 750 gallons of mash since a 750 gallon cook tank was available.

Capacity of the cooker can be determined by the volume of prepared mash obtained from one bushel of corn. Up to 35 gallons of water may be required to prepare one bushel of corn for fermentation. The volume of one

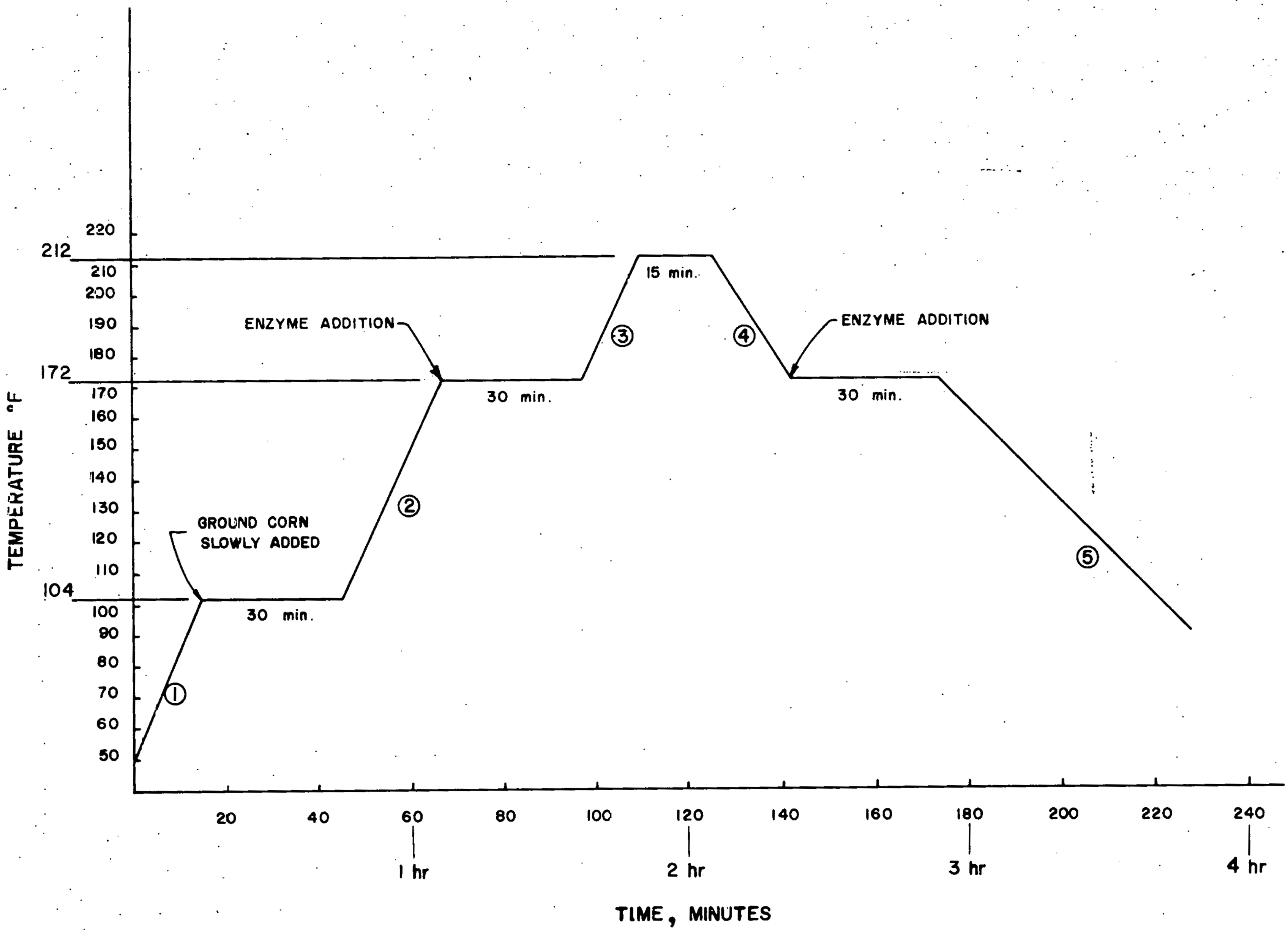

Figure 1: Cooking Times and Temperatures, TVA Farm-Scale Facility

bushel of corn in solution with water is approximately 4.8 gallons. Therefore, the maximum cook volume required per bushel of corn should be about 40 gallons. If live steam is used for heating, as in this application, the condensate must also be considered in determining final dilution rates.

An initial cook volume of 40 gallons per bushel of corn was used for this facility, and the volume of the cook tank was 750 gallons.

Then, to prepare approximately 750 gallons of mash,

$$\frac{750 \text{ gallons cook volume}}{40 \text{ gallons/bushel}} = 18.8 \text{ bushels of corn } (1{,}050 \text{ lbs})$$

are required, and the initial water needed is,

$$(18.8 \text{ bu})\ (20 \text{ gal/bu}) = 375 \text{ gallons}$$

This water will be added to the cooker and heated to 104°F. Assuming an initial water and corn temperature of 55°F, the heat input for heating water is determined by the following:

$$q = Mc\Delta T, \text{ where } c = 1 \text{ Btu/lb}\cdot{}^{\circ}\text{F for water}$$

By substitution into the above equation, q = 153,000 Btu. Following this heat-up stage, stirring is started and the corn is added to the cooker at a rate to prevent dough-balling. Additional heat will be required to raise the corn temperature from 55°F to 104°F. A specific heat of corn of 0.55 Btu/lb°F and a wet volume of 4.8 gallons per buchel was assumed (1). From the previous equation, heat input for the corn is 28,300 Btu. At this point, the initial water volume and corn are at 104°F as the process continues.

An alpha-amylase enzyme is added to the mash and the mash temperature is raised gradually from 104°F to 172°F. This heat requirement is 251,700 Btu's. The mash is held at 172°F for 30 minutes during which time the enzyme will begin to convert corn starch to glucose, maltose, and dextrin "limit." Gelatinization begins during this step and continues as the mixture is carried to its boiling point. The mash temperature is raised from 172°F to

212°F by adding additional heat (148,000 Btu's) and held at 212°F for 15 minutes. This sterilization destroys wild yeast cells and bacteria detrimental to the fermentation process. The mash is then cooled to 172°F by adding cold water. The heat to be removed is equivalent to the heat required to raise the temperature from 172°F to 212°F and the heat to be removed in cooling the steam condensate. The total cooling duty is then 172,000 Btu's (step 4, figure 1). The volume of water required to cool from 212°F to 172°F with an average cooling water temperature of 55°F can be determined from the following equation:

$$\text{Gallons } H_2O = \frac{q}{(8.33\ \text{lb/gal})\ c\Delta T}$$

In this case, 177 gallons of water are required. The total prepared mash volume at this stage, including 72 gallons of steam condensate, is about 715 gallons.

Live steam will be injected into the cook vessel with a perforated pipe. Steam from the boiler will be at 15 psig and 250°F with an enthalpy (h_g) of 1,164 Btu/lbm. The enthalpy of the saturated condensate at the following temperatures is as follows:

$T = 104°F$, $h_f = 72.0$ Btu/lbm

$T = 172°F$, $h_f = 140.0$ Btu/lbm

$T = 212°F$, $h_f = 180.0$ Btu/lbm

A constant steam rate is desirable for all cook tank heating steps to simplify control. Rates were determined for each heating step by the following procedure:

(1) The heat input for each step was adjusted to an assumed time interval.

(2) The heat requirement was divided by the energy available ($h_g - h_f$ @ T) for the appropriate temperature to determine the steam flowrate.

For example, for step 1, figure 1, the heat requirement is 153,000 Btu, and the steam requirement is determined as follows:

(1) For an assumed time interval of 15 minutes (or 0.25 hr) a Q is determined as;

$$Q = \frac{153{,}000 \text{ Btu}}{0.25 \text{ hr}} = 612{,}300 \text{ Btu/hr}$$

(2) The weight of steam required to heat water from 55°F to 104°F is

$$\frac{Q}{\Delta h} = \frac{612{,}300 \text{ Btu/hr}}{(1164\text{-}72) \text{ Btu/lbm}} = 561 \frac{\text{lbs steam}}{\text{hr}} \quad \text{or} \quad 9.4 \frac{\text{lbs steam}}{\text{min}}$$

The preceding analysis was repeated to determine the steam flow rate required to raise the mash temperature to 172°F in 20 minutes and then to 212°F in 15 minutes (steps 2 and 3, respectively, figure 1). Initial results were 12.3 and 10.0 lbs/min. As mentioned, a constant steam rate for all heating stages simplifies operation and control. The average of above three calculated flow rates, 10.5 lbs steam/minute, will be supplied to the system. Steam flowrate will be measured by an orifice plate flowmeter and the rate adjusted with a throttling valve. The time intervals for the various steps were calculated from the constant steam rate by the following equation:

$$\frac{Q}{(10.5)\text{x}(\Delta h)} - t \quad \text{such that}$$

Q = heat input for each step

Then, the time required (t) to raise the temperature of the initial water from 55°F to 104°F is 14 minutes, and to increase the mash temperature from 105°F to 172°F, 24 minutes, and from 172°F to 212°F, 15 minutes.

The exterior surface of the cook tank will be insulated to reduce conductive heat losses. Calculations based on summer and winter operation indicated heat losses less than 2,000 Btu for each temperature and time period required, and these losses were neglected in determining steam flow rates. The heat required to heat the corn and to maintain temperatures of 172°F and 212°F are minimal, and will be added intermittently as needed.

Mash Cooling

Once the mash has been cooled from 212°F to 172°F and held for the prescribed time, it is cooled to approximately 80°F for fermentation. To prevent further dilution, no additional cooling water can be added directly to the mash and appropriately sized cooling coils must be installed inside the cooker. The overall design heat transfer coefficients are calculated from the following procedure. Laboratory experiments were used according to the recipe to determine the mash viscosities at different temperatures. Agitator equipment specifications are included in the coil design, and a discussion of the agitator design will follow this section.

The following assumptions and criteria were used in the cooling coil design.

(1) Cooling water will be available at an average temperature of 55°F.

(2) Conductive heat losses to the environment will be minimal.

(3) The agitator diameter is 15.1 inches.

(4) The dimensions of the cook tank are 5.0-foot diameter by 6.5-foot height.

(5) The agitator speed is 233 rpm.

The cooling duty (step 5, figure 1) was determined as follows:

$Q_{coil} = (Mc\Delta T)_1 + (Mc\Delta T)_2$ where

$Mc\Delta T_1$ = heat contained in the water portion of the mash

$Mc\Delta T_2$ = heat contained in the corn portion of the mash

Substituting, and assuming the time allowed for cooling is one hour;

$$Q_{coil} = 473,600 \text{ Btu/hr}$$

Design procedures which follow are outlined in Kern (13).

The agitator creates a circulation regime defined by the Reynolds number:

$$Re_j = \frac{d^2 \eta \rho}{\mu}$$

In our case,

d = 1.26 ft (diameter of agitator)

η = 233 rev/min = 13,980 rev/hr

μ = 50 centipoise = 121 lb/ft-hr

ρ = 65.3 lb/ft^3 @ final dilution volume

and

$$Re_j = 11,980$$

Using Kern (13), figure 20.2, a heat-transfer coefficient from jackets and coils in agitated tanks is denoted by "j." For a Re_j = 11,980, "j" for a coil is 325.

The exterior heat transfer coefficient for the coil is obtained from the following:

$$h_c = j \frac{(k)}{D_t} (c\mu/k)^{1/3} (\mu/\mu_w)^{0.14}$$ where the previously undefined terms are;

k = thermal conductivity of mash

D_t = diameter of tank

μ_w = viscosity at tank wall,

then, substituting,

k = 0.33 Btu/hr ft$^2 \cdot$°F/ft

c = 0.92 Btu/lb·°F

$(\mu/\mu_w)^{0.14}$ = 0.95,

The above equation gives h_c = 142 Btu/hr·ft²·°F, which is the heat transfer coefficient for the exterior surface of the coil. Tube-side heat transfer coefficients for water are determined, knowing the flow velocity through the tubes and water temperature, from Kern (13), figure 25. In our case, the velocity is four ft/sec, average water temperature is 55°F, and the pipe diameter is two inches. For a 2.0-inch diameter tube, the inside heat transfer coefficient (h_i) is 640 Btu/hr·ft²·°F. Using these values and the procedure outlined in Kern (13), an overall design heat transfer coefficient (u) was determined to be 103 Btu/hr·ft²·°F.

The pipe surface area (A) required for a cooling duty (Q) is then,

$$A = \frac{Q}{(u)\ (\Delta T)} \qquad \text{where}$$

ΔT = logarithmic mean temperature difference (LMTD)

In this case, the pipe surface area required is;

$$A = \frac{473{,}584 \text{ Btu/hr}}{(103 \text{ Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F})\ \ (59^\circ\text{F})}$$

$$A = 78 \text{ ft}^2$$

The external surface area per linear foot of 2-inch schedule 40 carbon steel pipe is 0.622 ft². The total length of pipe required to provide the coil surface area is 125 feet.

The coil will be arranged in a vertical helical configuration as dictated by the physical characteristics of components which must be installed in the cook tank.

Cook Tank Agitation

Agitation of contents within the cook tank is essential. Turbine or propeller mixing devices may be installed vertically or horizontally in the cook vessel to mix the conditioned feedstock and aid in uniformly hydrolyzing the material. Incorporation of dry solids into a liquid is affected by particle size and wetting characteristics, rate and manner in which the dry feedstock is added, and amount and type of motion at the agitated surface. Although the heat transfer coefficient depends on the degree of agitation, sizing an agitator to achieve a specific heat-transfer coefficient is impractical. A reasonable design approach is to select an agitator that provides adequate bulk liquid motion, and then alter heat transfer area or other process conditions to achieve the desired result. This approach has been followed as reflected in the previous cooling coil design discussion.

Although a fairly wide variety of impellers is available from mixer manufacturers, a propeller agitator was selected for this facility. Axial flow is developed by a propeller with highest flow velocities parallel to the shaft. For maximum hydraulic efficiency, propellers should be machine cut, statically and dynamically balanced, and have a high-luster finish.

The basic specifications for a propeller agitator include the following:

(1) Speed in rpm

(2) Number of propellers on mixer shaft and location

(3) Propeller diameter(s)

(4) Horsepower of drive

(5) Drivehead style

(6) Materials of construction for submerged parts

(7) Positioning relative to the vessel

In positioning the agitator to the vessel, submerged shaft bearings were avoided in slurry concentrations containing solid particles.

For this facility, the final mash volume of the slurry to be agitated will be 750 gallons and the specific gravity of the mixture was assumed to be 1.1. The cook tank dimensions are 60-inch diameter and 78-inch straight side with a 6-inch deep dished bottom. The maximum process viscosity was measured in laboratory tests and found to be about 460 centipoises. These specifications were discussed with mixer manufacturer representatives, and a mixer with two steel propellers of 15.1-inch diameter on a 1.5-inch diameter steel shaft powered by a 2-hp motor was selected. The operating speed is 233 rpm, and the lower propeller is equipped with a stabilizing ring. The agitator unit will be a vertical drive assembly mounted on top of the tank.

Fermentation

The fermentation process follows the extraction of fermentable substrates from the desired feedstock. Substrates, or fermentable sugars, are innoculated with strains of yeast capable of withstanding 10 to 12 percent alcohol concentrations. At higher alcohol concentrations, the yeast cells begin to degenerate and a subsequent loss of alcohol conversion will occur. Sugar concentrations affect alcohol production. Excessively high concentrations can inhibit the growth of yeast cells. Problems with slow initial yeast growth can be lessened by using large innoculations. The yeast strain saccharomyces can effectively withstand 16-22 percent sugar concentrations and produce beer which ranges from 8-12 percent ethanol by volume.

Microbial contaminants can be a major problem because they can consume sugar, which reduces the amount of alcohol produced, and can drastically modify the fermentation conditions. Proper tank selection, construction, and sanitation techniques will eliminate most bacterial problems.

By using fermentation tanks separate from the cook tank, less expensive tank materials could be used. Assumptions and equipment requirements for the TVA facility include the following:

(1) Mild steel tanks may be used but will require a rust inhibitor paint and epoxy coating on the interior. Rust formations and pore spaces in the steel provide excellent locations for bacterial growth.

(2) Fiberglass tanks are generally acceptable, and plastic bulk tanks are accceptable if the material is alcohol tolerant. Plastic tanks may also be used for other purposes such as herbicide or fertilizer storage, depending on the periods of alcohol production and individual tank sizes.

(3) Tanks should be installed to allow complete drainage. Sloping support platforms may be required for flat-bottomed tanks.

(4) During fermentation, both carbon dioxide and heat are produced. Venting should be provided through a water seal to allow discharge of carbon dioxide without exposing tank contents to air. When ambient temperature exceeds about 90°F, cooling should also be provided, and can be accomplished with cooling coils or by spraying fermentation tanks.

(5) Pipe runs should be as short as possible. Dead-end piping segments must be avoided to improve sanitation and ease of cleaning and minimize pipe clogging.

(6) Tanks must be thoroughly cleaned before reuse for the next batch.

Based on these requirements, the following fermentation tanks and related equipment were selected for this evaluation facility:

(1) Polypropylene tanks, approximately 1,550 gallon capacity, with pipe fittings installed as required for loading, unloading, and venting.

(2) Flexible hose and quick-disconnect connectors will be used to transfer the mash from the cook tank to the fermenter.

(3) Flat bottom tanks will be installed on sloping platforms to facilitate drainage.

The equipment selected is available from most farm supply centers.

Distillation

Three methods of distillation were initially considered; (1) a "pot" still, (2) a vapor feed distillation column with an evaporator for the feed, and (3) a liquid feed distillation system. The "pot" still was eliminated because of the excessive distillation energy requirement and slow production rates. The vapor feed column has an even higher energy requirement due to the evaporator required (similar to a "pot" still), and the high reflux rate (35 to 40) required. A liquid feed distillation column operation was selected, and the design was developed using a 1,000 lb feedstock basis. The design was then scaled to a product rate of approximately 9 gallons per hour. Initial intentions were to have a product rate of 10 gallons per hour, but earlier calculations had indicated that, if an 8-inch column was to be the upper limit for our design (as specified by DOE), a design product flow rate of 9 gallons per hour is more reasonable. The distillation system is shown schematically in figure 2. The procedure used was determined from references (3,8,10,16). The design is presented here in brief form to indicate the type of procedure followed.

Feedstock Basis: 1,000 lbs at 8 volume percent ETOH

8 volume percent = 6.5 weight percent (see figure 8)

Thus: 65 lbs ETOH

and 935 lbs H_2O

Specification: Product is to be 190 proof; 95 volume percent ETOH

Production rate = 9 gallons/hour

Recover 95 percent of ETOH from F

Then, converting the 1,000 lb basis to moles, and determining mole fractions;

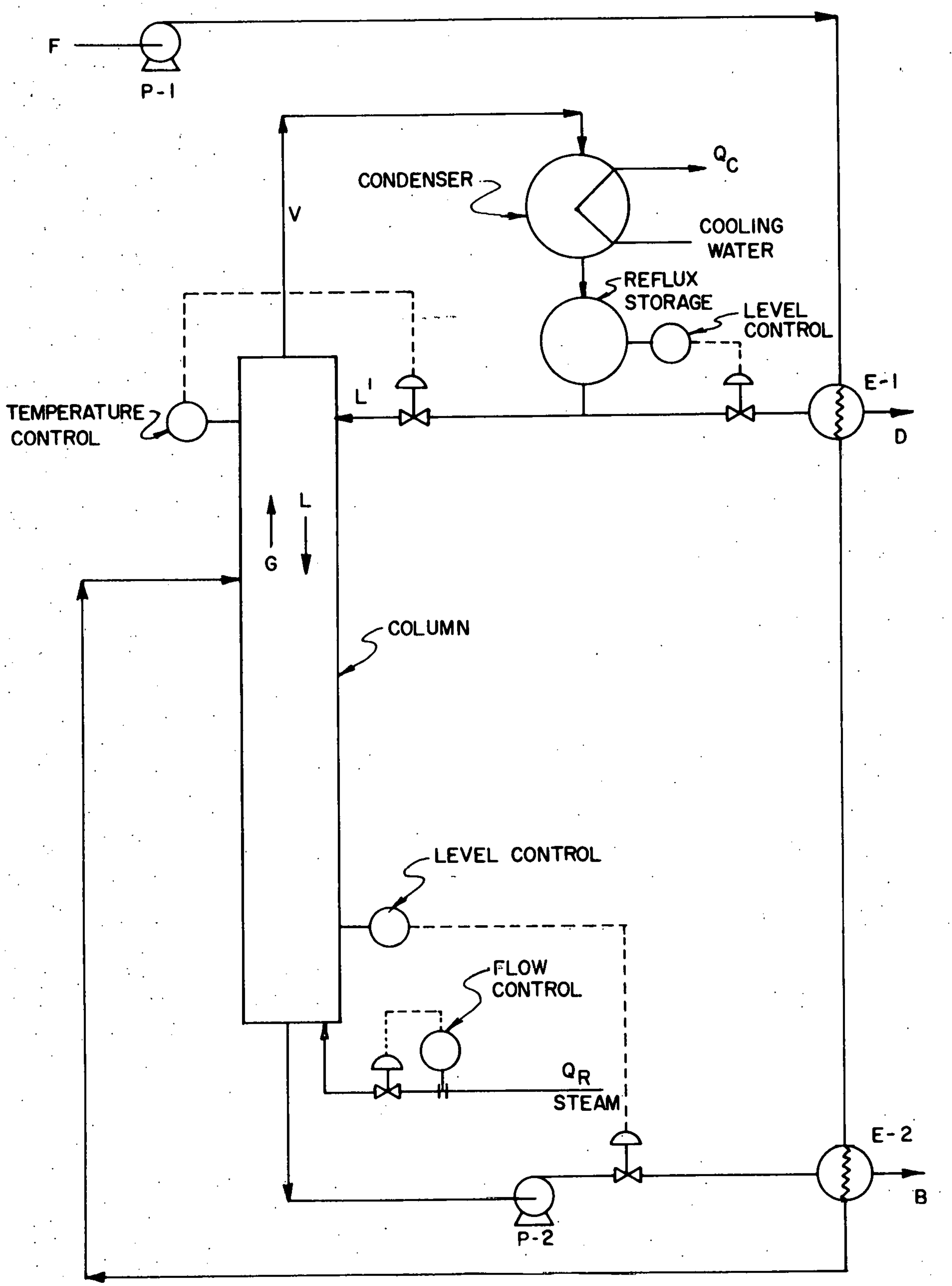

Figure 2: Schematic Representation of Distillation Column and Stream Nomenclature

$N_{ETOH,\ F} = 1.41$
$N_{H_2O,\ F} = 51.88$

$MF_{ETOH,\ F} = 0.026$
$MF_{H_2O,\ F} = 0.974$

$N_{ETOH,\ D} = 1.34$
$N_{H_2O,\ D} = 0.280$

where $MW_{ETOH} = 46.07$ and $MW_{H_2O} = 18.02$

To quantify D, using the equation;

$$(N_{ETOH})\ (MW) = \text{lbs ETOH},$$

then, D contains 61.7 lbs ETOH and 5.1 lbs H_2O

Then B = F-D

$N_{ETOH,\ B} = 0.07$, or 3.2 lbs
$N_{H_2O,\ B} = 51.60$, or 929.8 lbs

and

$MF_{ETOH,\ B} = 0.0013$
$MF_{H_2O,\ B} = 0.9986$

The mole fraction concentrations of the bottoms (B), and the product (D), are then plotted on a McCabe-Thiele diagram as shown in figures 3 and 4. Two scales, and thus two figures, were used for clarification of the lower mole fraction concentrations. We have assumed that F enters the distillation column as a saturated liquid. A minimum reflux ratio (L/D) can be calculated from:

$$(L/D)_{min} = \frac{X_d - Y_c}{Y_c - X_c}$$

where Y_c is the vapor mole fraction of E_{TOH} at the feed composition. In this case, and with X_d, Y_c, and X_c (from figures 3 and 4)

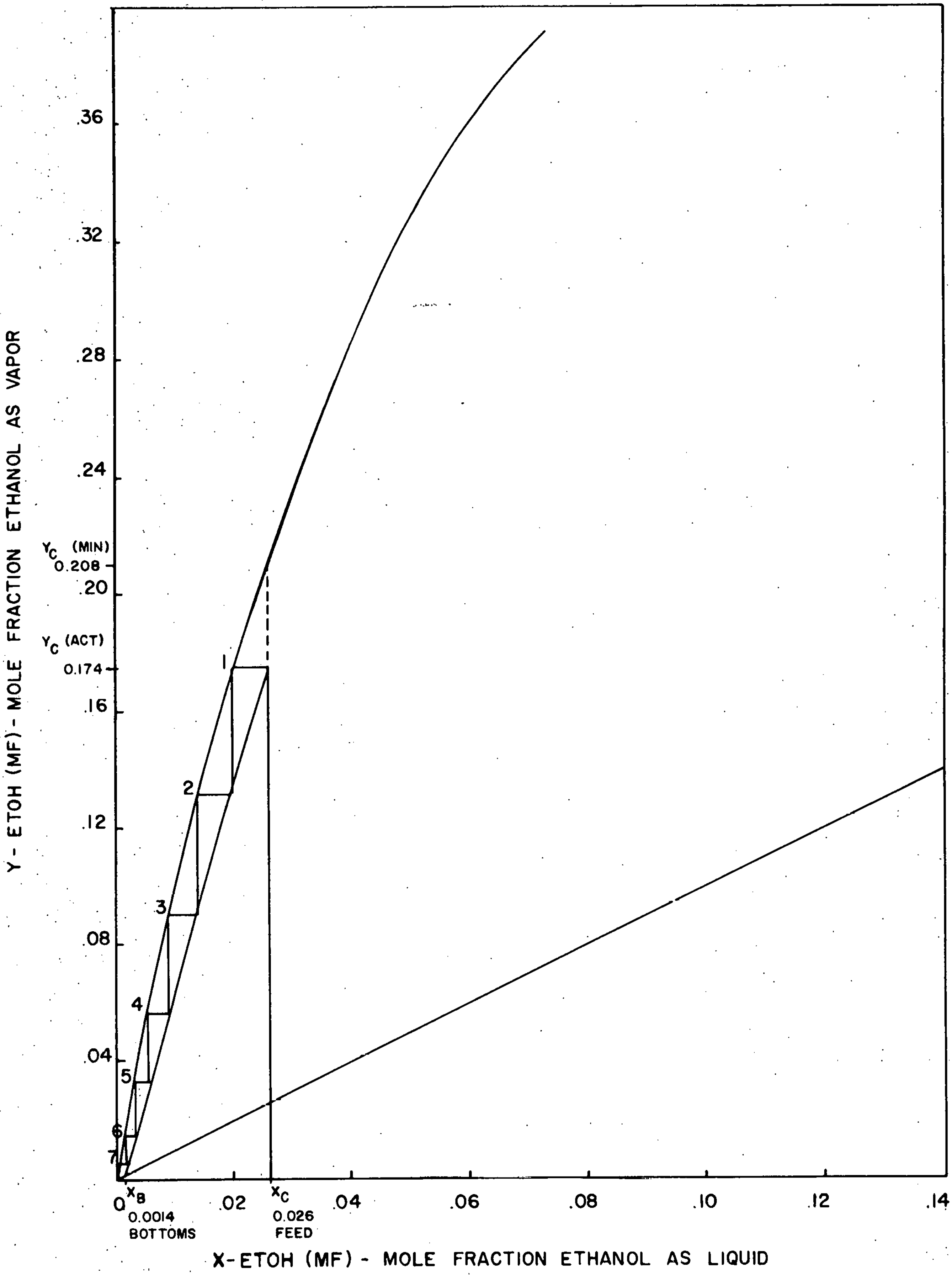

Figure 3: McCabe-Thiele Diagram-Below Feed, TVA Farm-Scale Facility

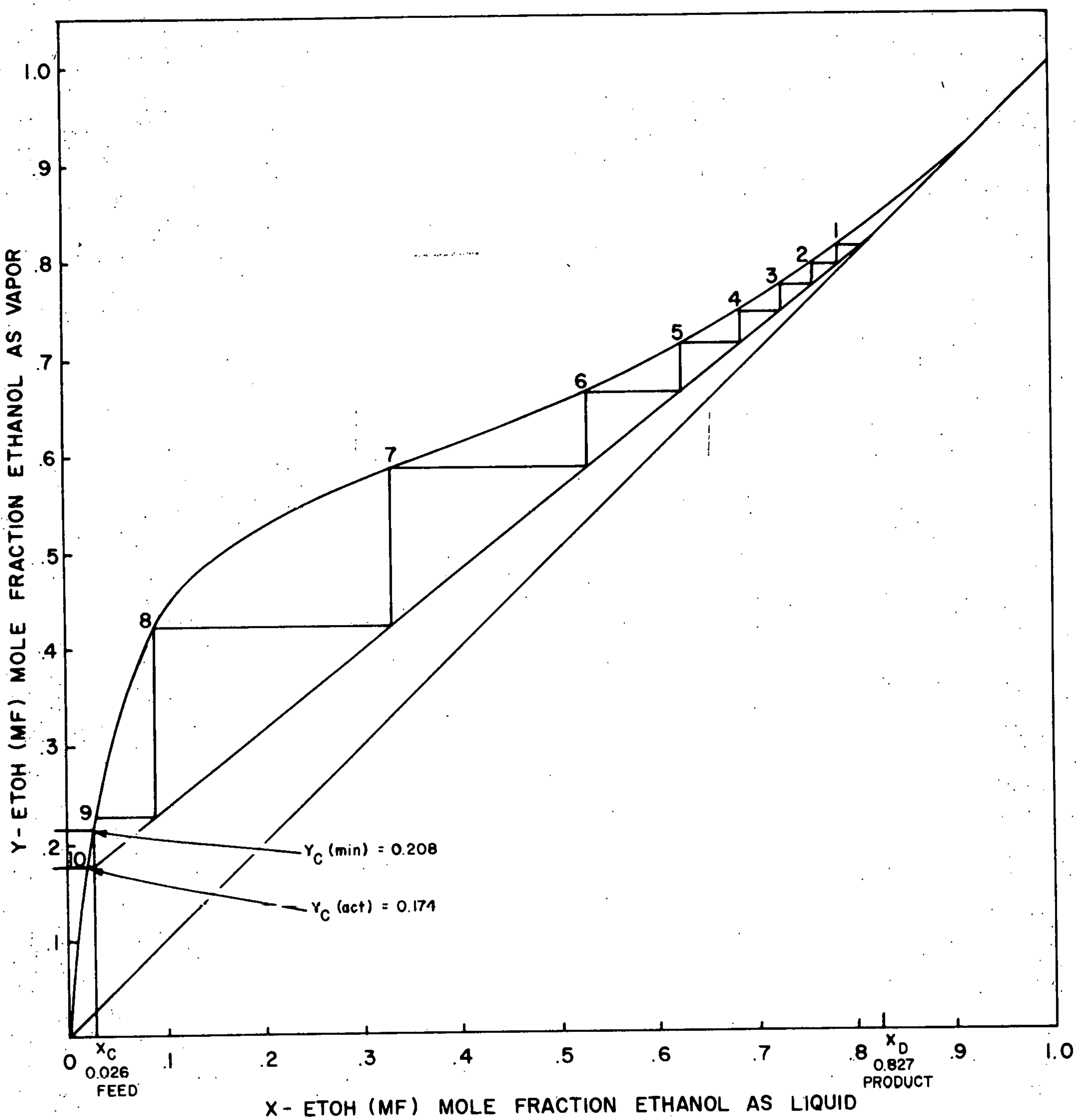

Figure 4: McCabe-Thiele Diagram-Above Feed, TVA Farm-Scale Facility

$$(L/D)_{min} = \frac{0.827 - 0.208}{0.208 - 0.026} = 3.4$$

Experience with distillation dictates the use of a multiplier of 1.3 to determine an actual reflux ratio (6). Using this multiplier,

$$(L/D)_{act} = 4.4$$

After solving for a new Y_c (0.174) for the actual reflux ratio and knowing compositions of B, F, and D, the number of theoretical stages can then be graphically stepped-off as shown in figures 3 and 4. An operating line is drawn on the McCabe-Thiele diagrams, using $(L/D)_{act}$ and the stream compositions. In this case, ten theoretical stages are required above the feed point, and five theoretical stages are required below the feed point. A time factor can now be entered into the design, and the various energy requirements can be established. Since the maximum column diameter was established by DOE as 8-inches, the product rate is limited to about 9 gallons per hour. Scaling for time with the desired product rate;

$$D = 60.9 \text{ lbs/hr or } 1.48 \text{ moles/hr}$$

Then, the reflux rate is,

$$L_R = (L/D)_{act}\ (D) = 268.5 \text{ lb/hr or } 6.5 \text{ moles/hr}$$

and the amount of vapor leaving the column is,

$$V' = L+D = 329.4 \text{ lb/hr or } 8.0 \text{ moles/hr}$$

The streams are quantified by component in table 1. With Q_R being the heating duty and Q_C the condenser duty, the energy balance for the distillation column can be written as:

$$Q_R = Q_c + (D)(H_d) + (B)(H_b) - (F)(H_f) + \text{losses}$$

Determining Q_c, $(D)(H_d)$, $(B)(H_b)$, and $(F)(H_f)$:

$$Q_c = (\text{lbs/hr ETOH})\ (\lambda\ \text{ETOH}) + (\text{lbs/hr } H_2O)\ (\lambda\ H_2O)$$

$$= 137{,}000 \text{ Btu/hr}$$

and, $(D)(H_d) = (\text{lbs/hr ETOH})\ (H_{ETOH,\ D}) + (\text{lbs/hr } H_2O)\ (H_{H_2O,\ D})$
$= 7{,}000$ Btu/hr

Similarly,

$(F)(H_f) = 131{,}700$ Btu/hr if F is preheated to 176°F through heat recovery from streams D and B (see pages 26 and 27).

and,

$(B)(H_b) = 155{,}700$ Btu/hr

Then,

$Q_R = 168{,}000$ Btu/hr + losses

If we add 10 percent for losses, the total distillation energy requirement is

$Q_R = 185{,}000$ Btu/hr

Table 1. Stream Composition and Flowrate

Stream	Component	Moles/hr	lbs/hr
F	ETOH	1.29	59.43
	H_2O	48.11	866.94
		49.40	926.37
D	ETOH	1.22	56.21
	H_2O	0.26	4.68
		1.48	60.89
L_R	ETOH	5.38	247.89
	H_2O	1.15	20.64
		6.53	268.53
B	ETOH	0.07	3.22
	H_2O	47.85	862.26*

*Steam injection will increase this figure.

Method of Heating

The distillation energy can be supplied either through a heat exchanger, or reboiler, or with live injection of steam. Major advantages of using a heat exchanger for heat include (1) bottoms are not further diluted, (2) heat rate is probably easier to control, and (3) condensate can be returned to the boiler. Using live steam has the primary advantages of not being subject to fouling with the bottoms and is also much less costly than using an exchanger. After consideration of these and other advantages and disadvantages of the alternative heating systems, a live steam injection heating system was chosen. A steam sparger will be located within the column to provide agitation and steam injection. The sparger will be moved above the liquid level if its use results in excessive foaming.

Stripping Section

Having determined Q_R, and assuming that, for live steam (@ 250°F, 15 psig) injection, the maximum vapor rate (G') through the stripping column is the steam injected,

$$G' = 190.5 \text{ lb/hr vapor flow}$$
$$= 0.053 \text{ lb/sec}$$

Next, a column diameter is normally selected. If the column diameter is not specified, a similar procedure can be used to size the column based on the desired production rate (10). In this case, an 8-inch diameter column was to be used if comparable with the desired flow rate of 9 gallons per hour. For an 8-inch column, the cross-sectional area (A) is 0.349 ft^2 and

$$G = \frac{G'}{A} = 0.152 \text{ lb/ft}^2\cdot\text{sec}$$

The maximum liquid flow rate is below the feed, or L_R + F.

$$L' = 55.9 \text{ moles/hr}$$

Assuming the maximum liquid flow rate is primarily composed of water, then

$$L' = 0.28 \text{ lb/sec}$$

and,

$$L = 0.80 \text{ lb/ft}^2\cdot\text{sec}$$

The density of the liquid, ρ_L, is taken as 59.8 lb/ft^3 and the density of the vapor, ρ_G, is 0.037 lb/ft^3.

At this point the column internals may be selected as either sieve trays or as distillation column packing. Considerable disagreement exists as to the better design. Factors such as fabrication cost, maintenance, likelihood of fouling, and distillation efficiency must be considered. A packed stripping and rectifying section was selected for evaluation in this facility, primarily based on the much lower cost and ease of maintenance associated with packing in a column this small. Based on recommendations of chemical engineers and others, fouling should not be a factor if a packing is properly selected. Fouling and efficiency of the packings to be evaluated may necessitate later conversion of this facility to the more expensive sieve trays.

Having chosen to use packing, the next step is to select a packing and determine a packing factor Fp. Since the feed will contain the slurried particles from corn, a large size packing was assumed to be less affected by solid particles as pore space would be larger. According to Norton (10), the packing nominal diameter should be less than 1/10 of the column diameter.

Initially, 3/4-inch nominal size ceramic Intalox saddles were selected, with Fp = 145 (table 2). The values needed to determine a pressure loss from figure 5 were determined,

$$\frac{G^2 \ Fp \ \mu^{0.1}}{\rho_g(\rho_l - \rho_g)} = 1.32$$

and

$$\frac{L}{G}\sqrt{\rho_g/\rho_l} = 0.025,$$

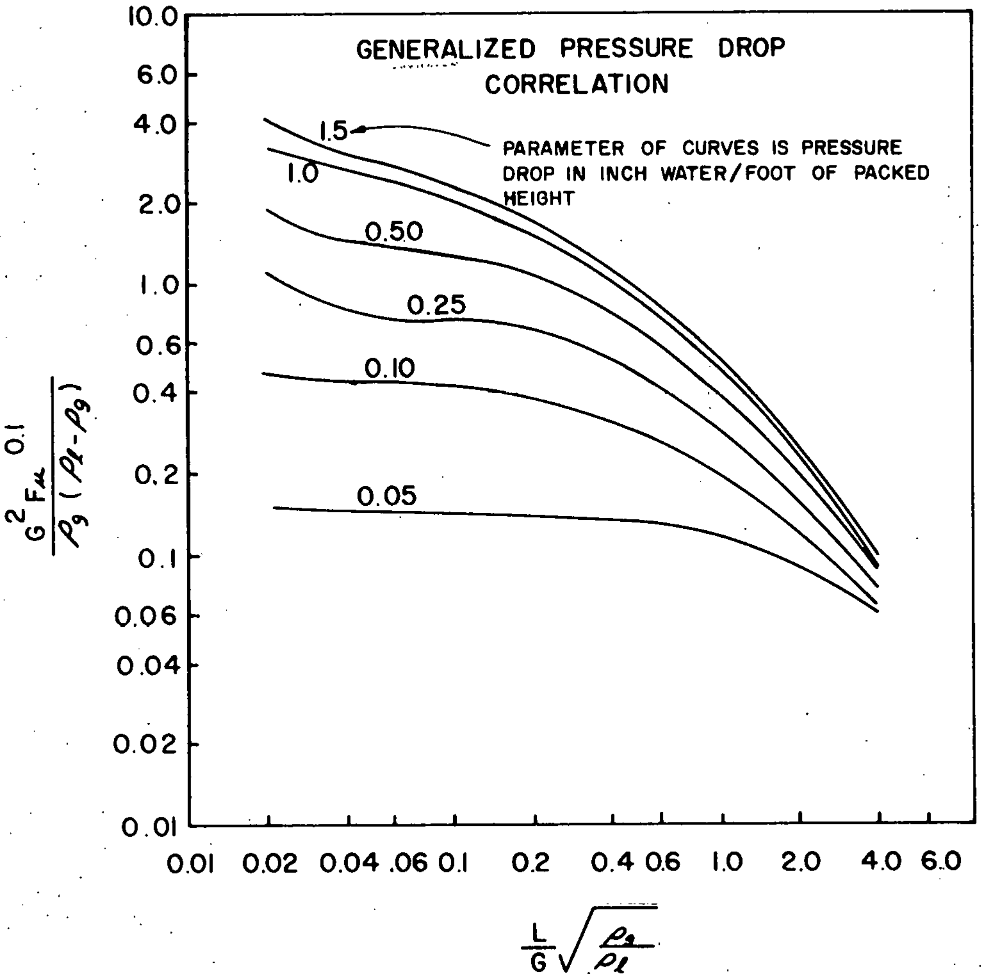

Figure 5: Generalized Pressure Drop Correlation in Packed Towers

where

μ = 0.28 centistokes

The values were used to determine a predicted pressure drop of 0.40 inch of water/foot of packed height from figure 5. This pressure drop is acceptable. If a larger packing is needed to help alleviate clogging problems with the mash, a 1-inch nominal size plastic super Intalox saddle may improve operations. The packing factor is 33. This packing has a 1:8 packing-to-tower diameter ratio, which is slightly above the recommended packing size. Calculating,

$$\frac{G^2 \; Fp \; \mu^{0.1}}{\rho_g(\rho_l - \rho_g)} = 0.30$$

the pressure drop from figure 5 is about 0.08 inch of water/foot.

The actual packing depth was then determined from figure 6, which was developed from table 2. For the 3/4-inch nominal size packing, the height equivalent to a theoretical stage (HETS) is selected as 1.25 feet. Then the packing depth required would be the number of theoretical stages, 5, times 1.25 feet, or 6.25 feet.

Table 2. Packing Factors (F_ρ) for Tower Packing: Wet and Dump Packed Nominal Packing Sizes (in.)

Type of packing	Material	1/4	3/8	1/2	5/8	3/4	1	1 1/4
Intalox saddles	Ceramic	725	330	200	-	145	92	-
Intalox saddles	Plastic	-	-	-	-	-	33	-
Super Intalox	Ceramic	-	-	-	-	-	60	-
Super Intalox	Plastic	-	-	-	-	-	33	-
Pall rings	Plastic	-	-	-	97	-	52	-
Pall rings	Metal	-	-	-	70	-	48	-

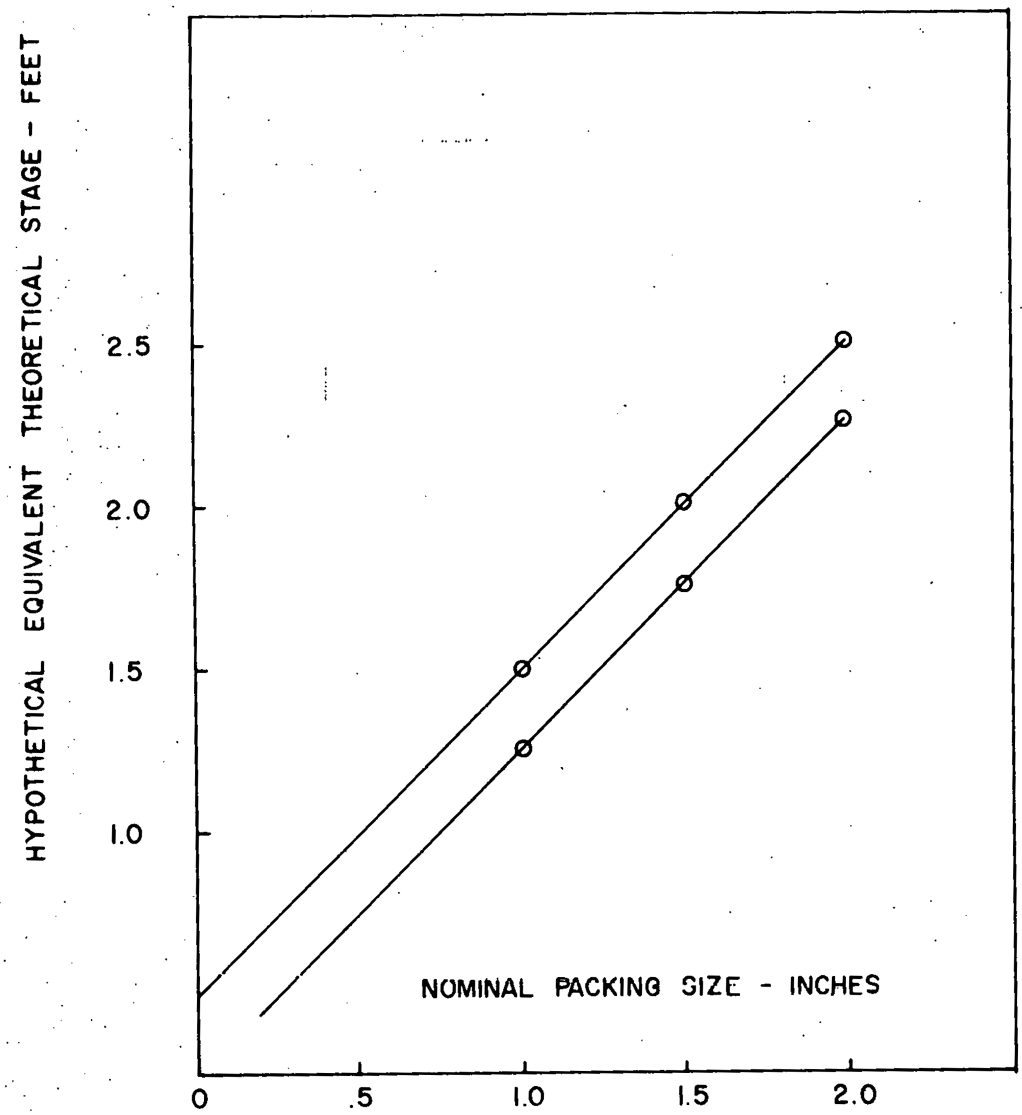

Figure 6: Generalized Height of Packing for One Theoretical Distillation Stage

Rectifying Section

A distillation tower packing will also be used in the rectifying section. For the 8-inch diameter column, the vapor and liquid rates are

$$L' = L_R = 268.5 \text{ lb/hr}$$

$$G' = V' = 329.4 \text{ lb/hr}$$

For the given diameter,

$$L = 0.213 \text{ lb/ft}^2 \text{ sec}$$

$$G = 0.262 \text{ lb/ft}^2 \text{ sec}$$

and

$$\rho_g = 0.089 \text{ lb/ft}^3$$

$$\rho_1 = 47.7 \text{ lb/ft}^3$$

$$\mu = 0.51 \text{ centistokes}$$

Then, in order to use figure 5, a packing factor must be selected. Plastic pall rings, 5/8-inch nominal size, $F_\rho = 97$, were selected. Entering figure 5 with

$$\frac{L}{G}\sqrt{\rho_g/\rho_1} = 0.038$$

and

$$\frac{G^2 \; Fp \; \mu^{0.1}}{\rho_g(\rho_1-\rho_g)} = 1.46$$

a pressure drop of 0.50 inch of water/foot of packing is read, which is acceptable. The next step is to determine the HETS (figure 6). For the 5/8-inch nominal packing size, the HETS chosen was 1.125 feet. Since 10 theoretical stages were required, the packed column height required is 11.25 feet.

If the column is operated for several days at a time, some provision for removing fusel oils will be needed. In a tray column, this is accomplished by periodically bleeding small amounts of liquid from the proper tray in the rectifying column. In a packed column, a tray (or trays) may be added for this purpose.

The stripping and rectifying sections will be separated, primarily to keep the total height of the facility comparable with a conventional building and for ease of support and access during evaluation and documentation.

Materials Section-Major Components

Many materials can be used, with the primary differences being in their relative cost, compatability with ethanol and water mixtures, expected life, and availability. Stainless steel and copper are compatable with the beer and product, and all have been used in ethanol production facilities. But these materials are also quite expensive and may not be widely available to farmers. Mild steel and plastic pipe, tanks, and fittings are widely available and relatively inexpensive; however, the mash and product are less compatable with mild steel, and significant corrosion is likely. Some plastics are compatable with the streams, but are not suitable for some processes at higher temperatures. With cost of the facility of major importance for a farm scale unit that will not be used continuously, the following materials were selected for major components of this evaluation facility.

Cook tank - mild steel coated with an epoxy finish on the interior, or stainless steel. (A surplus stainless steel tank will be used.)

Fermentation tanks - plastic fertilizer tanks (polypropylene).

Distillation columns, reflux drum, and product storage - mild steel.

Condenser and heat exchangers (except cook tank cooling coils) - brass and/or copper.

Cook tank cooling coils - mild steel.

Condenser Selection

The condenser duty has been earlier determined to be 137,000 Btu/hr. Several alternative methods of condensing were considered. Initially, a commercial air cooled radiator-type condenser was considered to reduce the amount of cooling water needed in the facility, but was later abandoned due to the high cost (> $2,000). Truck radiators were also considered since they cost less than a commercial condenser, but a radiator with the required surface area could not be located. This method of condensing may be pursued after initial operation of the facility.

A shell-and-tube condenser will be used in the evaluation facility. In an effort to reduce the amount of cooling water needed, the vapors will be introduced on the shell side and the product will be removed from condensate drain ports on the unit purchased. This will allow the use of cooling water on the tube side, and should allow higher cooling water ΔT's since the tubes can be periodically cleaned to help alleviate fouling and scale buildup.

The condenser was selected to meet the following specification:

Specification: Duty - 140,000 Btu/hr

Condensing 25.3 lbs H_2O and 304.1 lbs ETOH per hour

Entering vapor and exiting liquid at approximately 173°F

Cooling water available at 85°F, and can take a temperature rise of 30°F

Assumptions: u = 125, since cooling water may be fouling

Using procedures in Perry (16), a shell-and-tube condenser with a single pass configuration and a bare tube surface area of 15.6 ft^2 was selected.

Heat Recovery Aspects

The energy required in converting agricultural crops to fuel alcohol is significant. Energy balances are very important, as is the source of fuel for the cooking and distillation processes. Heat economy must be used where practical.

Two heat recovery and reuse concepts have been included in this facility. These include (1) using condenser and/or fermentation tank cooling water for initial feedstock preparation to decrease heating requirements during cooking, and (2) recovering heat from the product stream (D) and the bottoms stream (B) to be used in preheating the column feed (F) (see figure 2).

If the product stream (D) is cooled to 95°F by preheating the feed (F), a heat savings of 3,800 Btu/hr would be realized. Since the flow rates are quite low, turbulent flow conditions are needed for good heat transfer, and the solid particles in the mash preclude the use of very small tubes, a concentric pipe heat exchanger made with copper tubing will be used. The heat exchange surface area required is 1.5 ft^2. A 9.2 foot, 1/2-inch copper tube inside a 3/4-inch copper tube gives the required surface area.

Recovering heat from the bottoms (B) offers greater heat economy, since about 80,000 Btu/hr could be recovered in heating the feed to 177°F. The low flow rates, high velocities needed, and fouling characteristics of the two streams make the use of a shell-and-tube heat exchanger questionable. A concentric pipe exchanger, again made from copper tube, will also be used. Although a rather large surface area for heat exchange is required (19.7 ft^2), the exchanger will be fabricated with standard tube and fittings because of low cost and ease of cleaning. A 1/2-inch copper tube inside a 1-inch copper tube, with a total length of 120 feet will be required.

Pumps

All pumps used in the fuel alcohol plant must be capable of providing the correct process flow rate at the design system head. A smooth, even flow is preferred over pulsating flows to minimize system disturbances and control problems. It should be possible to locate all pumps in the plant so that they have a flooded suction to eliminate self priming.

If control requirements call for variable flow capability, either variable speed drives or nonpositive displacement pumps capable of throttling must be used. Variable speed drives are usually more energy efficient but are also more expensive.

Safety regulations require that the system be explosion proofed (see safety section). To meet this requirement either explosion proof electric motors or hydraulic or air motors must be used. Hydraulic and air motors can easily have their speeds varied by controlling the flow of fluid or air to them but are more cumbersome than electric motors.

Pumps to transport the beer/mash mixture, in addition to the above requirements, must be capable of handling a slurry with these properties:

(1) 4-10 percent ethanol

(2) 90-96 percent water

(3) Up to 34 percent solids of 20 mesh particle size

(4) Temperature 50-90°F

(5) pH 3.5-7.0

(6) Viscosity ~ 20-50 cp

(7) Mildly abrasive

Pumps to transport the stillage slurry (when mash is sent through the column), in addition to the head and flow rate requirements, must be capable of handling a slurry with similar properties:

(1) < 1 percent ethanol

(2) 99 + percent water

(3) Up to 34 percent solids of 20 mesh particle size (percentage is reduced if distillation is by steam injection)

(4) Temperature 210-212°F

(5) pH 3.5 to 7.0

(6) Viscosity ~ 20 cp

(7) Mildly abrasive

(8) Small amounts of fusel oils, etc.

If the column is "broken" to reduce overall height, a pump must be used to transport liquid from the bottom of the second column to the top of the first (to create the effect that the columns are still one). This pump must be capable of pumping dilute ethanol-water mixtures at temperatures between 170 and 212°F and with a viscosity of approximately 0.35 cp. Small amounts of fusel oils, etc., are also in the solution.

If a reflux or product pump is used, it must be capable of handling concentrated ethanol solutions (up to 192 proof) at temperatures up to 173°F. Use of a reflux pump permits the condenser and reflux drum to be placed below the top of the column thus allowing easier access to these components and minimizing supports required. The product will also contain small amounts of fusel oils and other impurities.

The slurry pumps selected for this facility will be air-driven diaphram-type pumps. The stripper column reflux pump will be an air-driven gear pump. No reflux or product pumps will be used. At 20 psi airline pressure, air consumption will be approximately 2 cfm for each diaphram pump and 4 cfm for the column reflux gear pump.

Piping

Proper pipe selection requires that the pipe be compatible with its environment on both sides of the pipe wall. Of major concern are compatibility of fluid and pipe material and temperatures and pressures involved.

PVC piping is recommended where temperatures are below 125°F except for piping acids and bases for pH control and where heat tracing is needed. Although some plastics may be suitable to transport acids and bases, stainless steel should be used for this application to ensure pipeline integrity and personnel safety. Only 304 SS should be used for sulfuric acid. If sodium hydroxide is used for pH control, then carbon steel is best used for piping. Above temperatures of 125°F, carbon steel pipe or copper tubing may be used for process material transfer. Steam lines must be A-106 carbon steel and of sufficient schedule for the temperatures and pressures involved.

Piping subject to wide temperature variations must have provisions for expansion and contraction. Care must be taken in running plastic piping to heat transfer components, since a flow stoppage may allow unsafe temperatures to build up and heat to be conducted back along the pipeline.

Instruments and Controls

Many control schemes will provide effective column control. However, the best systems use proportional controls and maintain all parameters as steady as possible. Sensitivity of the controls and system response are also important overall factors. Extremely sensitive controls may cause problems and are usually expensive. Also, all column controls must be explosion proof. In general, the following parameters must be controlled: (1) process temperatures, (2) process pressures, and (3) material flows.

Condensate temperature is controlled by the flowrate of the condenser cooling water. Excessive or supercooling of condensate wastes energy and can prevent proper temperatures in the column top due to refluxing. To achieve a 190 proof product, the top of the rectifying column needs to be held at that mixture boiling point temperature at atmospheric pressure. At the column bottom, maintaining a temperature just below the boiling point of water will minimize ethanol losses with the stillage. Boiling point temperatures will vary depending on operating pressure. Higher pressures will elevate the boiling points of ethanol and water; lower pressures will lower them. Systems operated at atmospheric pressure must take into account the boiling point for the site elevation.

With the exception of vacuum stills, most on-farm systems operate with 2-3 psig at the base of the stripper column and atmospheric pressure at the top of the rectifying column. This pressure difference provides the driving force to move the alcohol vapor through the column. Safety valves of sufficient capacity must be provided to prevent excessive pressure buildup (over 30 psig) in the event of blockages.

The condenser is normally equipped with a vent to permit equalization of pressure and to provide escape of noncondensable gases. The vent for this application will be one-quarter inch coiled copper tubing, vented to the outside (for safety purposes). The coil will cool and condense escaping alcohol vapors and drain the condensate back to the column.

Figure 2 shows a simple control scheme based on material balance with feed entry and steam flow at a constant rate. Reflux flow rate is regulated by an automatic valve controlled by a temperature sensor located at mid-column. Level controls in the reflux drum and column bottoms control material flows from the columns.

The control system chosen for this facility is shown in figure 7. It is similar to figure 2 except that reflux is based on level control. If

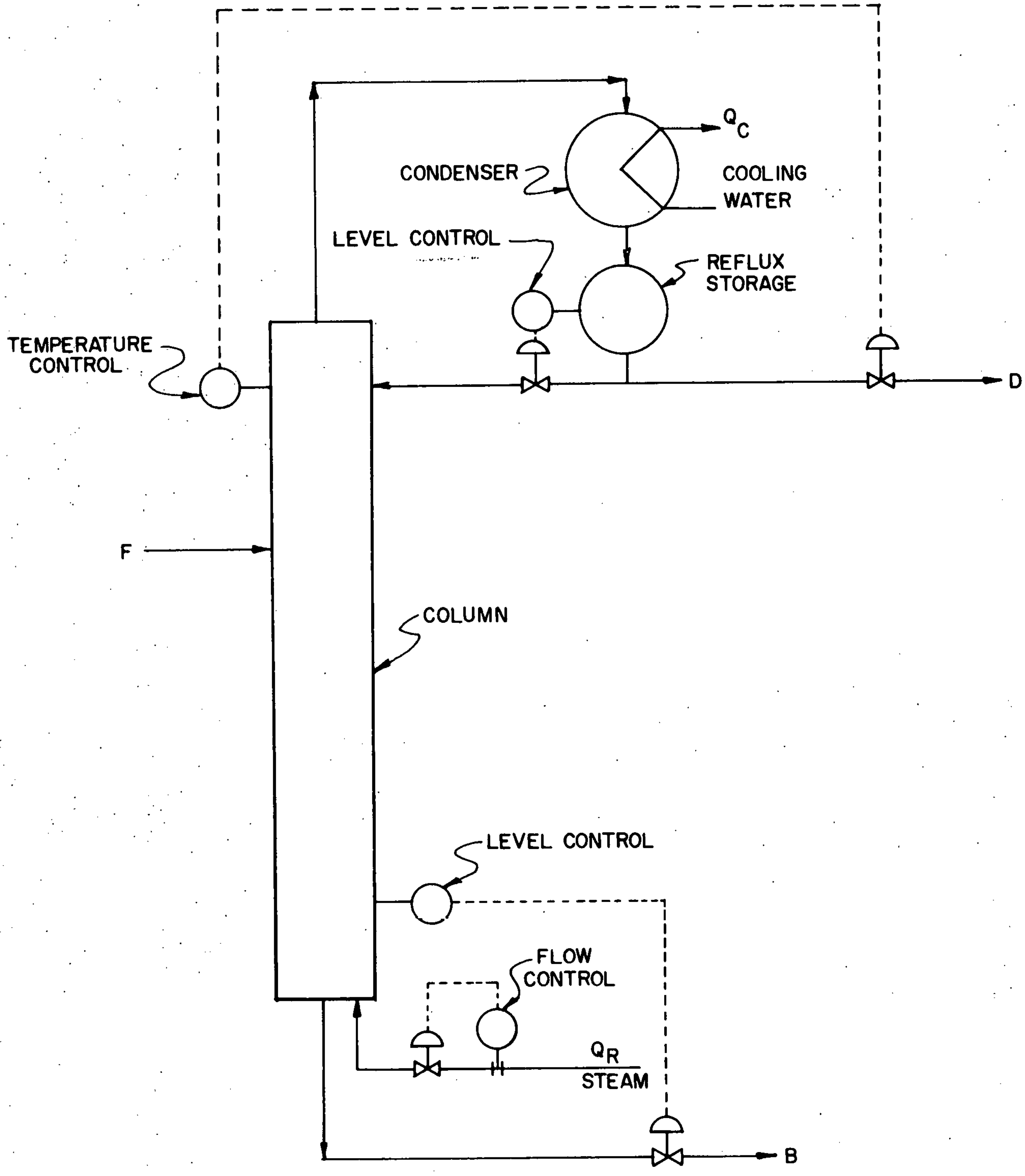

Figure 7: Schematic Representation of the Distillation Control System, TVA Farm-Scale Facility

column top temperature is too high, the high vapor flow will result in more condensate. The level control (which may be a simple standpipe), will reflux more liquid to be revaporized, and the column temperature will be reduced. Column temperature below the desired temperature has the converse effect. The use of this control scheme simplifies column startup since no product will be dispensed until the column top temperature is correct. Thus, no manual adjustment is necessary at startup and a high proof product is assured from the start.

The steadier all parameters can be maintained, the easier the control process (to a point) and the greater the process efficiency. Column insulation helps the control system by reducing temperature variations due to heat exchange with surroundings. This is more important for columns located outside.

Instruments to indicate process conditions and determine if the system is functioning at design conditions. They are also used for manual adjustment of process controllers, system startup, and experimental purposes. Column temperatures and pressures and process flowrates are indicated by instruments. All should be easily readable from ground level and, preferably, from one location.

Temperatures may be indicated with thermometers of the proper range (150-250°F for column applications) and graduations of at least 2°F or less. Pressure gauges must be suitable for operation at the temperatures involved and have a range of 0-30 psig with minimum graduations of 2 psi. Most standard pressure gauges are suitable for high temperature applications if the gauge is connected to the process with a cooling "pigtail." Steam flows can most economically be monitored with orifice plates. Other process fluid flows can most easily and economically be measured with rotameters. Selection of rotameters must take into account flowrates as well as physical properties of the fluid or slurry as listed in the section on pumps.

Steam System Requirements

The goal was to select a steam boiler system that could be fired by renewable fuels. Coal was not a suitable fuel for this facility because expensive scrubbers were required to meet EPA emission standards. Some wood-fired boilers can meet emission standards depending on the grade of fuel and if the conbustion unit is adjusted and maintained properly. Wood-fired boilers that burn small particles of wood are desirable as fuel flow rate can be varied to control boiler temperature. Boilers meeting these requirements require more physical space for installation. Also, it is difficult to locate and buy boilers of less than 100 hp that are economical and meet these requirements.

A low pressure steam system was desired to avoid licensing requirements and the need for a boiler operator. Low-pressure systems are less expensive but are limited to 250°F and 15 psig. Package boilers are preferred because of their ease of installation.

Safety features required on any boiler system are pressure/temperature gauges, approved pressure relief valve, high limit pressure or temperature shutoff, water level indicator, and manually resettable low water shutoff. An alarm is also desirable. A boiler with automatic controls that varies fuel feedrate to control boiler temperature is preferred and necessary if the entire system is to be automated.

Steam is used in the fuel alcohol plant for cooking, distillation, and sterilization. Cooking is best done by steam injection because the mixtures readily scorch and cake on heat transfer surfaces. If the mash is sent through the column, distillation is best accomplished by steam injection for the same reason. Live steam injection equipment is also normally less expensive than heat exchangers. If steam is injected into the column, it should be dried first to maximize efficiency. A trap is required on the bottom of the dryer to drain off condensate. The amount of condensate will be very minimal (less than 5 percent of the steam flow) and will not justify the expense of returning it to the boiler for small scale systems. If a reboiler is used for distillation, its condensate must be returned to the boiler to maintain system efficiency.

All boiler feedwater will require some treatment to provide maximum boiler life. If steam injection is used, this treatment is limited to water softening (where necessary) as other chemicals are incompatible with the process. The boiler system chosen for this application is manufactured by Rettew Associates and has an output of 700,000 Btu/hr of 15 psig, 250°F steam. The system can burn wood chips, sawdust, ground corncobs, or similar material and consists of a fuel storage bin, fuel conveyor furnace, and boiler. The furnace can be throttled to 25 percent of maximum output (corresponding to distillation steam requirements) without losing the fire. Fuel flow is automatically controlled to maintain steam pressure.

SAFETY CONSIDERATIONS

Ethanol is classified as a Class IB flammable liquid. The flash point temperature is 55°F, the boiling point is 173°F, and the vapors are heavier than air. Hazardous locations in the areas surrounding the ethanol containing components and other hazardous materials, such as sulfuric acid and gasoline, are covered in applicable sections of the National Fire Protection Association codes. Basically, these codes address safety considerations of (1) storing ethanol and other hazardous materials, including storage location and venting requirements, (2) the use of explosion proof electrical devices in hazardous locations, (3) fire extinguisher needs, (4) relief venting or pressure relief requirements for process components, and (5) ventilation requirements for locations in buildings. If a boiler is used, applicable codes must be followed in its construction and operation.

In addition to codes and standards for the process and storage components, electrical wiring and boiler, efforts must be made to allow for personnel safety. Proper safety equipment, such as glasses, hard hats, and protective clothing should be used where applicable. Emergency showers and eye-wash stations should be located near hazardous materials. Local safety switches and shrouding should be provided for all conveyors, augers, and other similar equipment. Piping containing hazardous or hot materials should be color coded and labeled. Guardrails should be provided for elevated work platforms.

Proper precautions must also be taken to prevent accidental or intentional human consumption of the ethanol produced since the facility does not produce a beverage quality alcohol. Labeling of containers as poisons and adequate instruction of personnel should help prevent these type safety problems.

It is very important that the operator know proper and safe operating procedures, process hazards involved, ways to handle accidents, and where safety equipment is located and how it is used. Proper attention to safety will reduce insurance premiums and minimize personnel risk and injury.

REFERENCES

1. Agricultural Engineers Yearbook. American Society of Agricultural Engineers. St. Joseph, Michigan. 1978.

2. A Learning Guide for Alcohol Fuel Production. National Alcohol Fuel Producers Association. 1979.

3. Aerstin, Frank and Gary Street. Applied Chemical Process Design, Plenum Publisher. 1978.

4. Baumeister, T. (ed.). Marks' Standard Handbook for Mechanical Engineers, McGraw-Hill. 1967.

5. Biocon (US). Technical and Product Information. Lexington, KY.

6. Culberson, Oran. University of Tennessee. Personal Communication. 1980.

7. Crombie, Lance. Making Alcohol Fuel; Recipe and Procedure. Rutan Publishing Co. 1979.

8. "Design Information for Packed Towers." Norton Company. Akron, OH. Bulletin DC-11. 1979.

9. Fuel from Farms, A Guide to Small-Scale Ethanol Production. Solar Energy Research Institute. February 1980. (SERI/SP-451-519-UC-61).

10. Hengstebeck, R. J. Distillation Principles and Design Procedures. Krieger, 1976.

11. Hicks, Tyler G. (ed.). Standard Handbook of Engineering Calculations. McGraw-Hill. 1972.

12. Hoffman, Harold L. "Automatic Control for Distillation." Hydrocarbon Processing Petroleum Refiner. February 1963. vol. 42. No. 2. p 107-122.

13. Kern, Donald Q. Process Heat Transfer. 1st Edition, 1950.

14. Kirk, Raymond and Donald Othmer. Encyclopedia of Chemical Technology. John Wiley, 1979.

15. Parker, Norman H. "Mixing, Modern Theory and Practice on the Universal Operation." Chemical Engineering. June 8, 1964, p. 165-203.

16. Perry, Robert A. and Cecil H. Chilton. Chemical Engineers' Handbook. McGraw-Hill. 1973.

17. "Small Scale Fuel Alcohol Production." United States Department of Agriculture. Washington, DC. March 1980.

REFERENCES
(Continued)

18. Weast, Robert C. (ed.). CRC Handbook of Chemistry and Physics, The Chemical Rubber Company. Cleveland, OH.

19. Weber, A. P. "Selecting Propeller Mixers." Chemical Engineering. September 2, 1963, p. 91-98.

20. Yaws, Carl L. and Jack R. Hopper. "Physical and Thermodynamic Properties-Methanol, Ethanol, Propanol, and Butanol." Chemical Engineering. June 7, 1976, p. 119-127.

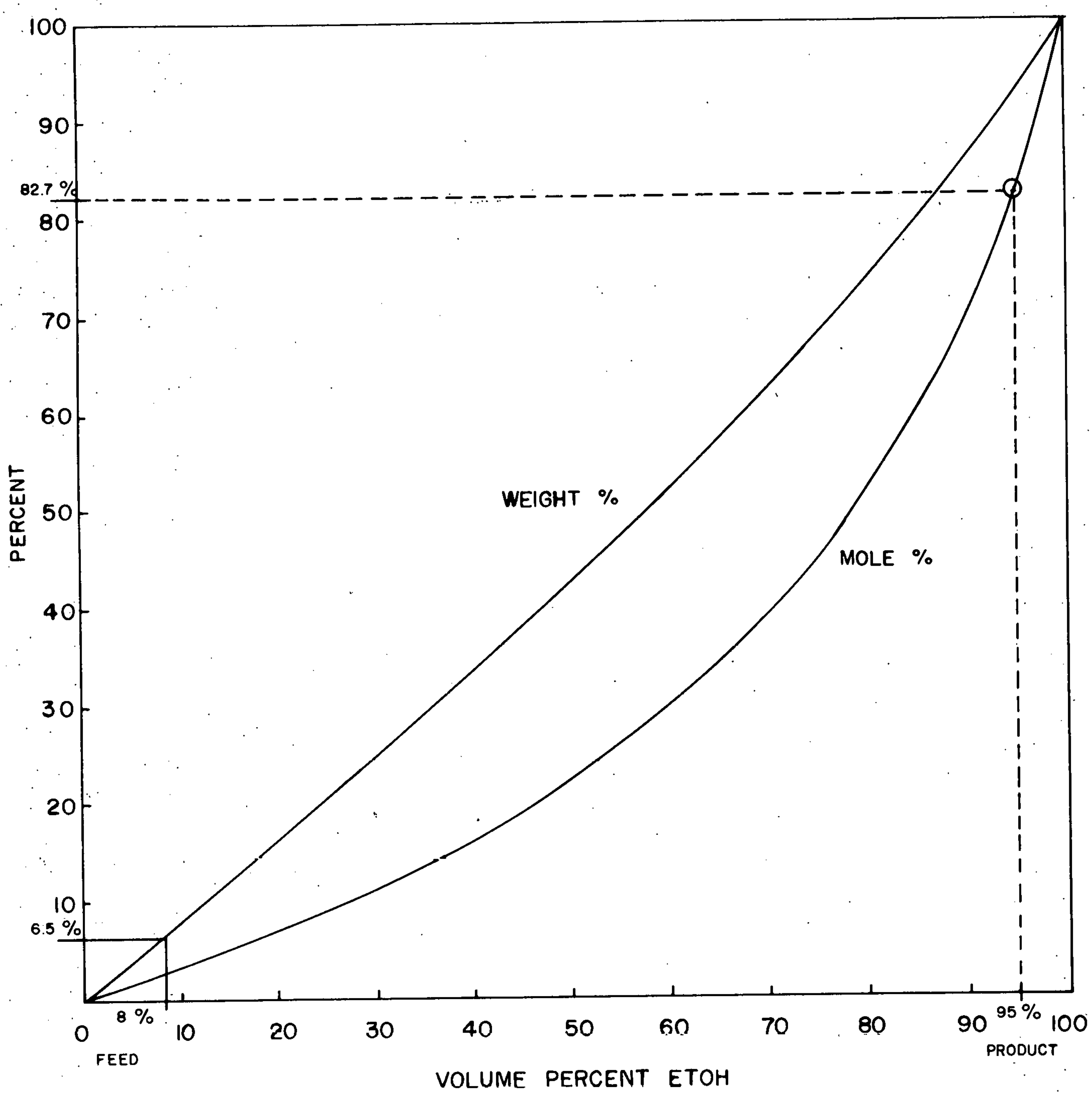

Figure 8: Relationship of Weight Percent and Mole Percent for Ethanol and Water

GLOSSARY OF TERMS

Alcohol: The family name of a group of organic chemical compounds composed of carbon, hydrogen, and oxygen; a series of molecules that vary in chain length and are composed of a hydrocarbon plus a hydroxyl group, CH_3-(CH_2)n-OH; includes methanol, ethanol, isopropyl alcohol, and others.

Aldehydes: Any of a class of highly reactive organic chemical compounds obtained by oxidation of primary alcohols, characterized by the common group CHO, and used in the manufacture of resins, dyes, and organic acids.

Alpha-Amylase - Amylase: Enzyme which converts starch into sugar.

Ambient: The prevalent surrounding conditions usually expressed as functions of temperature, pressure, and humidity.

Anhydrous: A compound that does not contain water either absorbed on its surface or as water of crystallization.

Anhydrous Alcohol: 200-proof alcohol; contains no water.

Atmospheric Pressure: Pressure of the air (and atmosphere surrounding us) which changes from day to day; it is about 14.7 psia.

Azeotrope: The chemical term for two liquids that, at a certain concentration, boil at the same temperature; alcohol and water cannot be separated further by distillation at this concentration.

Batch Fermentation: Nutrient mixture and micro-organisms are allowed to ferment from start to finish in a single vessel.

BATF: Bureau of Alcohol, Tobacco, and Firearms; under the U.S. Department of Treasury. Responsible for the issuance of permits for the production of alcohol.

Beer: The product of fermentation by micro-organisms; the fermented mash, which contains about 8 to 12 percent alcohol, usually refers to the alcohol solution remaining after yeast fermentation of sugars.

Beer Still: The stripping section of a distillation column for concentrating ethanol.

Beta - Amylase: See amylase.

Boiling Point: The temperature at which the transition from the liquid to the gaseous phase occurs in a pure substance at constant pressure.

British Thermal Unit (Btu): The amount of heat required to raise the temperature of one pound of water one degree Fahrenheit under stated conditions of pressure and temperature (equal to 252 calories, 778 foot-pounds, 1,055 joules, and 0.293 watt-hours); a standard unit for measuring quantity of heat energy.

Bulk Density: The mass (weight) of a material divided by the actual volume it displaces as a whole substance expressed in lb/ft^3; kg/m^3; etc.

Carbohydrate: A chemical term describing compounds made up of carbon, hydrogen, and oxygen; includes all starches and sugars.

Carbon Dioxide: A gas produced as a byproduct of fermentation; chemical formula is CO_2.

Column: Vertical, cylindrical vessel used to increase the degree of separation of liquid mixtures by distillation or extraction.

Condenser: A heat-transfer device that reduces a thermodynamic fluid from its vapor phase to its liquid phase.

Continuous Fermentation: A steady-state fermentation system that operates without interruption; each stage of fermentation occurs in a separate section of the fermenter, and flowrates are set to correspond with required residence times.

Cooker: A tank or vessel designed to cook a liquid or extract or digest solids in suspension; the cooker usually contains a source of heat and is fitted with an agitator.

Denature: The process of adding a substance to ethyl alcohol to make it unfit for human consumption; the denaturing agent may be gasoline or other substances specified by the Bureau of Alcohol, Tobacco, and Firearms.

Dextrins: A polymer of D-Glucose which is intermediate in complexity between starch and maltose formed by hydrolysis of starches.

Dextrin "Limit": A polysaccharide obtained from starch by the action of heat and enzymes.

Dextrose: The same as glucose.

Direct Fermentation: The term used to describe the fermentation of complex carbohydrates by micro-organisms. Implies a lack of hydrolysis to simple sugars before fermentation.

Disaccharides: The class of compound sugars which yield two monosaccharide units upon hydrolysis; examples are sucrose, mannose, and lactose.

Distillate: That portion of a liquid which is removed as a vapor and condensed during a distillation process.

Distillation: The process of separating the components of a mixture by differences in boiling point; a vapor is formed from the liquid by heating the liquid in a vessel and successively collecting and condensing the vapors into liquids.

Enzymes: The group of catalytic proteins that are produced by living micro-organisms; enzymes mediate and promote the chemical processes of life without themselves being altered or destroyed.

Ethanol-C_2H_5OH: The alcohol product of fermentation that is used in alcohol beverages and for industrial purposes; chemical formula blended with gasoline to make gasohol; also known as ethyl alcohol or grain alcohol.

Evaporation: Conversion of a liquid to the vapor state by the addition of latent heat of vaporization.

Feed Plate: The theoretical position in a distillation column above which enrichment occurs and below which stripping occurs.

Feedstock: The base raw material that is the source of sugar for fermentation.

Fermentable Sugar: Sugar (usually glucose) derived from starch and cellulose that can be converted to ethanol (also known as reducing sugar or monosaccharide).

Fermentation: The growth of micro-organisms in a nutrient medium under reduced oxygen tension; or a micro-organically mediated enzymatic transformation of organic substances, especially carbohydrates, generally accompanied by the evolution of a gas.

Fermentation Ethanol: Ethyl alcohol produced from the enzymatic transformation of organic substances.

Flash Point: The temperature at which a combustible liquid will ignite when a flame is introduced; anhydrous ethanol will flash at 51°F, 90-proof ethanol will flash at 78°F.

Fractional Distillation: A process of separating alcohol and water (or other mixtures).

Fusel Oil: A clear, colorless, poisonous liquid mixture of alcohols obtained as a byproduct of grain fermentation; generally amyl, isoamyl, propyl, isopropyl, butyl, isobutyl alcohols and acetic and lactic acids.

Gelatinization: The rupture of starch granules by temperature which forms a gel of soluble starch and dextrins.

Glucose: A monosaccharide; occurs free or combined and is the most common sugar; chemical formula $C_6H_{12}0_6$.

Glucosidase: An enzyme that hydrolyzes any polymer of glucose monomers (glucoside). Specific glucosidases must be used to hydrolyze specific glucosides; e.g., B-glucosidases are used to hydrolyze cellulose; a-glucosidases are used to hydrolyze starch.

Heat Exchanger: A device that transfers heat from one fluid (liquid or gas) to another, or to the environment.

Heat of Condensation: The same as the heat of vaporization, except that the heat is given up as the vapor condenses to a liquid at its boiling point.

Heat of Vaporization: The heat input required to change a liquid at its boiling point to a vapor at the same temperature.

Heating Value: The amount of heat obtainable from a fuel and expressed, for example, in Btu/lb.

Hydrolyze: The process of decomposition involving splitting of a bond and addition of water.

Hexose: Any of various simple sugars that have six carbon atoms per molecule.

Hydrometer: A long-stemmed glass tube with a weighted bottom; it floates at different levels depending on the relative weight (specific gravity) of the liquid; the specific gravity or other information is read where the calibrated stem emerges from the liquid.

Inoculum: A small amount of solution produced from a pure culture which is used to start a new culture.

Liquefaction: The change in the phase of a substance to the liquid state; in the case of fermentation, the conversion of water-insoluble carbohydrate to water-soluble carbohydrate.

Mash: The mixture of sugars, nutrients, and water that is capable of being fermented by micro-organisms. Usually refers to alcohol production by yeast.

Monosaccharides: See Fermentable Sugar.

Packed Distillation Column: A column or tube constructed with a packing of ceramics, steel, copper, or plastic material to provide higher reflux efficiencies per unit volume.

pH: A term used to describe the free hydrogen ion concentration of a system; a solution of pH 0 to 7 is acid; pH of 7 is neutral; pH over 7 to 14 is alkaline.

Plate Distillation Column: (Sieve tray column): A distillation column constructed with perforated plates or screens.

Proof: A measure of ethanol content; 1 percent equals 2 proof; 100-proof ethanol is 50 percent alcohol and 50 percent water. Ethanol (100 percent) is 200 proof.

Rectification: With regard to distillation, the selective increase of the concentration of the lower volatile component in a mixture by successive evaporation and condensation.

Rectifying Column: The portion of a distillation column above the feed tray in which rising vapor is enriched by interaction with a countercurrent falling stream of condensed vapor.

Reflux: To condense back on oneself; to effect higher purity or concentration by condensation and reevaporation repeatedly in a distillation column.

Renewable Resources: Renewable energy; resources that can be replaced after use through natural means; example: solar energy, wind energy, energy from growing plants.

Residue: Part which remains after part is taken.

Saccharify: To hydrolyze a complex carbohydrate into a simpler soluble fermentable sugar, such as glucose or maltose.

Saccharomyces: A class of single-cell yeasts which selectively consume simple sugars.

Sieve Tray Column: A distillation column constructed with perforated plates or screens (see plate distillation column).

Sight Gauge: A clear calibrated cylinder through which liquid level can be observed and measured.

Simple Sugars: Molecules of carbohydrate namely monosaccharides and disaccharides, such as glucose, galactose, mannase, sucrose, or fructose, etc; (see fermentable sugars).

Specific Gravity: The ratio of the mass of a solid or liquid to the mass of an equal volume of distilled water at 4°C.

Starch: A carbohydrate polymer comprised of glucose monomers linked together by a glycosidic bond and organized in repeating units; starch is found in most plants and is a principal energy storage product of photosynthesis; starch hydrolyzes to several forms of dextrin and glucose.

Still: An apparatus for distilling liquids, particularly alcohols; it consists of a vessel in which the liquid is vaporized by heat, and a cooling device in which the vapor is condensed.

Stillage: The liquid products or waste remaining after distillation of a beer. The soluble residue--water, proteins, etc.

Stripping Section: The section of a distillation column below the feed in which the condensate is progressively decreased in the fraction of the more volatile component.

Sucrose: A crystalline disaccharide carbohydrate found in many plants, mainly sugar cane, sugar beets, and maple trees; $C_{12}H_{22}O_{11}$.

Vaporize: To change from a liquid or a solid to a vapor, as in heating water to steam.

Vapor Pressure: The pressure at any given temperature of a vapor in equilibrium with its liquid or solid form.

Wort: The liquid remaining from a brewing mash preparation following the filtration of fermentable beer.

Yeast: Single-cell micro-organisms (fungi) that produce alcohol and CO_2 under anaerobic conditions and acetic acid and CO_2 under aerobic conditions; the micro-organism that is capable of changing sugar to alcohol by fermentation.